AN INVESTIGATION OF THE EFFECTS OF AN ELECTRICAL FIELD ON FLAMEHOLDER STABILITY

BY

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TABLE OF CONTENTS

ABSTRACT

The introduction of high velocity, continuous flow propulsion systems has intensified the search for methods of flame stabilization. One of the more generally accepted methods of accomplishing stabilization has been by the use of a small obstruction placed in the combustion chamber, known as a flameholder.

This investigation studied the additional stabilizing effect that a direct current electrical field might have on flame stabilization by means of a flameholder. The investigation was conducted in the low range of fuel-air ratios.

It was found that the direct current electrical field, for the fuel-air ratios used, increased the blowout limit of the flameholder, the maximum fuel-air mixture velocity at which combustion could be maintained at the flameholder, by a maximum of 9%.

This investigation was conducted by LT H.E. Van Ness, USN, in the Graduate School of the Mechanical Engineering Department, Rensselaer Polytechnic Institute, Troy, New York, from February to June, 1950.

INTRODUCTION

The trend in any type of propulsion power units is almost invariably toward the development of a more powerful unit. In recent years the advent of the continuous flow combustion types of propulsion units has introduced many new and challenging problems. Since these machines, with few exceptions, are essentially air handling machines, the constant demand for more and still more power has raised the problem of stabilizing a flame in a high velocity gas stream.

It has been shown that a flame may be more readily stabilized in a rapidly moving air stream by the introduction into the airstream of an obstruction known as a flameholder. Reference 1. Considerable study has gone into the development of flameholders and results have generally not been published for security reasons.

This investigation proposes to augment the stabilizing property of the flameholder with an electrical field. That flames have many interesting electrical properties is well known, and considerable work has been done in investigations by many scientists over a long period of years. These studies have led to some

well-founded conclusions, but there has also been considerable variance of other results. It was in the study of flame propagation under turbulent flow conditions that it was noticed that there was a large increase in the blow-off limits of Bunsen flames under the influence of an electrical field. Reference 2.

This investigation will concern the blow out limits of lean mixtures of an electrically stabilized flameholder.

This investigation was carried out by the author from February to June, 1950, in the graduate division of the Department of Mechanical Engineering, Rensselaer Polytechnic Institute, Troy, N. Y.

THEORY

A flame is visible evidence of a chemical reaction that has interested man for centuries. It has only been in the last sixty years that scientific methods have been sufficiently accurate to warrant confidence in experimental results. In spite of the tremendous advances made since then some of the fundamental occurrences in flames are not clearly understood. One of these zones of incomplete knowledge concerns the subject of ions in flames. Conclusions reached by the most respected investigators vary widely, in some cases as much as one thousand percent. This is due principally to the inherent difficulty of the problem.

As this thesis is based upon ion properties, the lack of confirmation of most of the fundamental numerical values of ions in flames and the complexity of the problem makes a numerical theoretical development difficult. Therefore no time will be wasted in a numerical theoretical development, the results of which would be in question. However, a short discussion of the theory underlying this investigation is necessary if it is to be understood.

In order to clarify the discussion that follows it will be well to define several terms that will be used.

1. Flame- gas rendered luminous by heating or by the liberation of chemical energy.
2. Flame front - boundary surface between the luminous region and the dark region of unburned gas.
3. Reaction zone - A region of inhomogeneity adjacent to the flame front in which homogeneous unburned charge is transformed into combustion products in chemical equilibrium.
4. Spacial velocity - the velocity at which a flame front moves in a direction normal to its surface relative to a fixed point.
5. Transformation velocity, V_t - the velocity at which the flame front advances into and transforms the unburned charge in a direction normal to its surface.
6. Gas velocity, V_g - the velocity at which the unburned gas moves in space normal to the flame front.
7. Mixture velocity, V_u - the velocity at which the unburned gases move in space.

Consider a flow of premixed fuel and air down a tube to a region where the combustion reaction is to take place. It is necessary that the temperature of the unburned mixture be raised to its ignition temperature before the combustion reaction can take place. After ignition by the introduction of heat from an outside

source, as a spark, this temperature rise in the gas mixture adjacent to the reaction zone is the result of heat of combustion being released in the reaction zone. The initial reaction results in the formation of a variety of combustion products. Among these are products known as chain carriers and chain breakers. A chain carrier is a combustion product that reacts with substances in the immediate area to continue the reaction. A chain breaker is a reaction product that does not react after being formed. Surfaces also serve as chain breakers by reacting with chain carriers. The relative numbers of chain breakers and chain carriers determine the speed at which a reaction will proceed. For example, explosive reactions contain a great preponderance of chain carriers.

Flameholders became necessary in high velocity constant flow combustion chambers because of the relatively low velocity of flame transformation. The region immediately downstream from the flameholder is a region of relatively slow moving turbulent gas. Thus, it serves as an excellent flame anchor. Just how far the flame front advances from this region of slow moving gases depends principally upon the velocity of the unburned gases approaching the flame front. If the transformation

velocity is less than the gas velocity, the flame front will reach an equilibrium position as shown in Fig. 1.

From Fig. 1 it can be seen that

$$\cot\theta = \frac{V_p}{V_g}$$

and

$$V_p = \left[V_u^2 - V_g^2\right]^{1/2}$$

so

$$\theta = \cot^{-1} \frac{\left[V_u^2 - V_g^2\right]^{1/2}}{V_g}$$

$$= \cot^{-1} \left[\frac{V_u^2}{V_g^2} - 1\right]^{1/2}$$

but at equilibrium

$$V_t = V_g$$

so

$$\theta = \cot^{-1} \left[\frac{V_u^2}{V_t^2} - 1\right]^{1/2}$$

Thus it can be seen that the larger the value of V_u the smaller the value of θ.

This will cause the flame area behind the flameholder to become quite small. In actual practice (see Photographs 1 and 2) the boundaries of the flame, though not clearly defined, seem to parallel the sides of the flameholder for a considerable distance downstream from the flameholder. It is necessary that the combustion reaction be continued in this region as in all other regions. The velocity of the unburned gas is greater

than the transformation velocity so that without the anchored portion of the reaction zone behind the flameholder the entire reaction would be swept away and extinguished by dilution of the fuel air mixture by air and/or reduction of temperature by excess air.

Thus it can be seen that the combustion reaction must be kept in operation immediately downstream from the flameholder or the reaction will come to an end. The difficulty of this is further increased by three conditions: (1) the heat produced by this portion of the reaction is being carried away by the large volume of cool unburned gases passing essentially parallel to the flame front; (2) the flameholder surface at the upstream end of this anchored reaction zone is carrying away further heat by conduction; (3) the combustion reaction is being brought to a halt at the flameholder surface as the metal surface acts as a chain breaker.

Since these three effects are tending to bring the combustion reaction to an end, it would seem that one method of keeping the reaction moving forward would be to transport reacting material from the downstream portion of the reaction zone into this flame anchor zone. This reacting material would replace the heat and chain carriers being removed from the flame anchor zone by the cold unburned gas and the flameholder.

It was reported in reference 3 and 4 that intense ionization is taking place in the reaction zone with positive ions and free electrons being produced. The exact mechanism that produces these ions has never been fully understood. Recent studies have lead to the belief that the ions are produced by chemical effects in the reaction zone. Reference 5.

If sufficient energy could be given to the ions, it is possible that by means of collisions between the ions and reacting gas molecules, the gas molecules could be forced farther up into the flame anchor zone immediately downstream from the flameholder and around the flameholder tip. This would increase the supply of heat energy and chain carriers that are constantly being lost to the flameholder and the surrounding rapidly moving gas stream. Thus, the mixture velocity could be further increased before the flame would blow out.

It is proposed to impart energy to the ions by means of a d.c. field. The ions will receive this energy over their mean free path and upon collision with molecules of the gas mixture transfer this energy to all the molecules of the gas mixture. Only the positive ions will be considered since the small mass of the electrons will make them ineffective in transferring

energy by collision. References 2 and 5. The effect of the field, therefore, will be to give the ions and subsequently the molecules in the flame reaction zone a momentum in the direction of the electric field.

Consider a single positive ion.

$$\text{Energy} = \text{Force} \times \text{distance}$$

$$= X\, e\, \lambda \qquad \text{ergs} \qquad (1)$$

where

X = Field strength = stat volts/cm

e = electronic charge on positive ion in statcoulombs

λ = mean free path of ion in cm

Equation (1) represents the total energy given by the field to a single ion traveling its mean free path.

Then the total energy given by the field to the flame is

$$\text{Energy total} = X\, e\, \lambda\, NV$$

where

N = number of ions per cc of flames

V = volume of flame exposed to field

This energy absorbed may be kinetic energy of translation or other types, such as vibrational. It will be assumed that all of the energy absorbed from the electrical field is kinetic energy of translation.

Then the energy absorbed per second is:

Energy / time between collisions

In reference 6 it is shown that the time between collisions may be expressed as

$$t = \left[\frac{m\lambda}{2\,X\,e}\right]^{1/2} \tag{3}$$

where

m = mass of positive ion

then

$$\frac{\text{Total Energy}}{\text{second}} = \frac{X\,e\,\lambda\,N\,V}{\left[\frac{m\lambda}{2\,X\,e}\right]^{1/2}} \tag{4}$$

$$= \frac{2^{1/2}\,X^{3/2}\,e^{3/2}\,\lambda^{1/2}\,N\,V}{m^{1/2}} \tag{5}$$

Yarnold found, reference 6, that the drift velocity, the velocity of the ions in the direction of the electric field, was of the same order as the total velocity of the ions. It may be expressed as:

$$W = \text{drift velocity} = 1.1\left[\frac{X\,e\,\lambda}{m}\right]^{1/2} \tag{6}$$

Therefore

$$\lambda^{1/2} = \frac{w\,m^{1/2}}{1.1\,X^{1/2}\,e^{1/2}} \tag{7}$$

then substituting (7) in (5)

$$\frac{\text{total energy}}{\text{second}} = 1.285\,X\,e\,W\,NV \tag{8}$$

Also drift velocity may be expressed as

$$W = k X \qquad (9)$$

where

k = ion mobility = cm/sec/volt/cm

so substituting (9) in (8)

$$\frac{\text{total energy}}{\text{second}} = 1.285\ X^2 ekNV \qquad (10)$$

Therefore, to increase the effect of the electrical field on flame stability, it would seem that it would be beneficial to do the following:

1. Increase the field strength.
2. So place the electrical field that the maximum portion of the positive ions are exposed to the field.
3. Increase the number of positive ions.

Items 1 and 2 were used in this investigation. Item 3 was not used due to lack of time, but a method and apparatus sketch are included in the Recommendations.

APPARATUS

The equipment used in this investigation consisted of a centrifugal blower, delivering a constant air supply, a fuel supply of commercial heating gas, a mixing system, a combustion system of pipe and flameholder and a source of electrical energy. In addition, there were manometers, pressure gages and thermometers to measure the properties of the fluids at various stations. See Fig. 2.

The individual parts of the apparatus will now be described in more detail.

AIR SYSTEM

The air was supplied by a centrifugal blower which operated at approximately thirty-five hundred revolutions per minute. The air was delivered at a pressure of 26.2 ± .2 inches of water gage and remained at this value regardless of the amount of air used. This was of considerable value as it simplified the procedure used in the investigation.

A photograph of the blower is shown in Photograph 3.

AIR METERING SYSTEM

The amount of air used was measured by means of a sharp edged orifice 1.12 inches in diameter. This orifice

was installed in a three inch brass pipe leading from the centrifugal blower. Taps to read static pressure and differential pressure across the orifice were installed according to American Society of Mechanical Engineers' Specifications. Values of differential pressure and static pressure were read from water manometers. The temperature of the air was measured by a thermometer installed 16 inches downstream from the orifice.

AIR CONTROL SYSTEM

The amount of air used was controlled by a three inch gate valve installed 24 inches downstream from the sharp edged orifice.

This valve was of such construction that it gave minute control over the air passing through it. For example, it required 10 complete turns to move the valve gate from full closed to full open.

A photograph of the control valve is shown in Photograph 4.

FUEL SUPPLY

Fuel was supplied by a tank of commercial liquified fuel with the trade-name of Pyrofax. This fuel is 80% propane (C_3H_8) and has the following properties:

BTU/pound	21500
Specific Gravity (Air = 1)	1.56
Boiling Point	-44°F
Critical pressure	66.1 lbs/in^2
Ratio of specific heats	1.153
Vapor pressure at 72°F	132 lbs/in^2

This fuel supply was satisfactory in that it was easily controlled and readily available. However, it complicated procedure in that it did not maintain a constant pressure at the high rates of fuel flow used. This was accomplished by applying heat to the tank by a blowtorch as necessary.

A photograph of the system is shown as Photograph 5.

FUEL METERING SYSTEM

An orifice of diameter .11 inches was constructed and installed in a section of pipe. Flange tapes installed according to American Society of Mechanical Engineers' Specifications, were located so as to measure differential pressure across the orifice and static pressure of the fluid stream.

The method used to calibrate the orifice is described in the appendix.

Fuel flow was maintained at a high pressure (110 lbs/in^2) which eliminated any error which would have been caused

by the pressure of the air with which it was mixed if the fuel was throttled to a low pressure. The fuel was led to the mixing chamber by a high pressure rubber hose.

The differential pressure across the orifice was measured by a water manometer connected by copper tubing. Tank pressure and gas static pressure downstream from the orifice were measured by direct reading gages connected by copper tubing. This system is shown in Photograph 5.

MIXING SYSTEM

Fuel and air were mixed in a mixing chamber constructed from a pipe "Tee" fitting with one connection of the "Tee" fitting plugged. The shape of the chamber plus the ninety degree turn which the air had to make gave the air a degree of turbulence. Fuel was injected radially from a 3/8 inch diameter pipe through twelve .07 inch diameter holes. The end of this pipe was plugged.

A sketch of the mixing chamber is shown as Fig. 3. Also see Photograph 4.

COMBUSTION TUBE AND FLAMEHOLDER

The combustion tube consisted of a 1.5" diameter iron pipe. The purpose of the tube was to contain and direct the fuel-air mixture to the flameholder.

The flameholder consisted of a hollow fiber tube .5" in diameter tipped by a 3 inch plug of brass to which the flame impinged. An insulated wire ran up the hollow fiber tube and was connected to the brass flameholder tip by an Allen screw.

The flameholder was centered in the combustion tube by two sets of three centering screws tapped through the combustion tube wall. The flameholder projected .5" from the combustion tube. The insulated electric wire was also led through a gas tight gland in the combustion tube. The wire and centering screws aided in the mixing of the fuel-air mixture. A thermometer was inserted in the combustion tube 8.5" from the downstream end to measure mixture temperature.

A sketch of the cross-section of the flameholder and combustion tube is shown in Fig. 4. See also Photograph 6.

A sketch of the three configurations of anode and cathode used in this investigation are shown in Figs. 5, 6 and 7.

ELECTRICAL SYSTEM

The electrical system used consisted of a high voltage, low amperage supply produced by filament rectifiers and transformers from a 110 volt a.c. source. A wiring diagram is shown as Fig. 8.

A variable direct current voltage of from 0 to 17000 volts could be obtained with this system. A photograph of the electrical apparatus is shown as Photograph 7.

The positive lead from this machine was connected to the ring or round end rod anode. The negative lead was connected to the metal tipped flameholder and,in one arrangement,to the flameholder and the combustion tube.

The three electrical connections and anode-cathode configurations used are sketched in Figs. 5, 6 and 7.

The first configuration used consisted of a 6" diameter ring as anode and a square end flameholder tip as cathode. The ring anode had a rectangular cross-section. Se Fig. 5 and Photographs 8 and 9.

The second arrangement used was a 3 inch diameter ring anode and a rounded tip flameholder cathode. The anode had all sharp edges removed with file and emory paper. See Fig. 6 and Photographs 10 and 11.

The third configuration was a round end nod anode and two cathodes. One cathode was the round end flameholder tip and the other the combustion tube with the edges rounded. See Fig. 7.

PROCEDURE

This investigation was limited to very lean mixtures due to limitations of time and fuel supply. The fuel supply was such that high values of weight flow could not easily be maintained for any reasonable period of time.

Previous investigations with flameholders included a study of the blow off limit. This is defined as the maximum fuel-air flow at which some flame will impinge upon the sides of the flameholder. No study of the blow off limit was made in this investigation as the upstream portion of the flameholder was constructed of heat sensitive fiberboard for insulation purposes.. In studies of the blow off limit comparatively low values of mixture flow rates are used. If too low a value were used a bad flash-back might cause the flame to move into the combustion tube with resulting destruction of the upstream portion of the flameholder.

This investigation was therefore limited to a study of the blowout limit. The blowout limit may be defined as the fuel air mixture rate of flow at which the flame is blown away from the tip of the flameholder and is so extinguished.

It was desired to make each run at a certain fuel-air ratio. To do this it was necessary to construct Fig. A1 which gives the corresponding pressures to maintain across the fuel orifice and the air orifice to have the desired fuel-air ratio.

Fig. A1 was plotted from data in Table AIV. This data was computed by selecting a fuel-air ratio, say .04, assuming a value of fuel flow in lbs/sec, and computing the air weight flow. Then knowing the fuel and air weight flows, one can read the orifice differential pressures necessary to produce them from Figs. A2 and A3.

For each run the following procedure was used. A low weight flow of air would be set and increasing amounts of gas would be introduced into the air stream until the mixture could be lighted with a candle held at the flameholder. A fuel air ratio of either .04, .045, or .05 would be selected. The desired voltage would be set on the electrical apparatus. Then by the use of Fig. A1 the air and fuel orifice differential

pressures would be increased simultaneously by means of their respective control valves so that the same fuel-air ratio was maintained. Fuel and air flow, always in the same ratio, were increased until the flame blew out.

Throughout the run the fuel tank pressure was maintained at 110 lbs/in^2 gage by applying heat. Air static pressure would maintain itself quite constant at 26.5 in. H_2O gage. The air temperature would increase slightly during a run due to the work done on it by the blower and the heat energy released by the flame in the room, but for one run it could be considered oonstant. The air temperature between measured runs could be varied by opening or closing doors of the room or by running the apparatus to increase the room temperature.

No measure was made of gas temperature. It was believed that the low fuel-air ratios used would result in such comparatively small amounts of fuel being used that the temperature of the fuel would have a negligible effect upon the temperature of the air. To check this assumption a thermometer was placed in the combustion tube 8.5 inches from the end. It was found that this thermometer, which read mixture temperature, would indicate a mixture temperature of approximately two degrees below the air temperature. It was assumed that

radiation from the flame and hot parts of the flameholder would increase the mixture temperature another two degrees as it passed from the mixture thermometer to the combustion tube mouth. Therefore, the mixture was assumed to be at the same temperature as the air.

The principle difficulties encountered were:

(1) Maintaining the fuel pressure at 110 lbs/in^2 gage.

(2) Maintaining the air temperature at 110° F.

Limitations encountered included:

(1) Voltage limitations due to arcing between the cathode and anode.

(2) Fuel flow limitations due to equipment.

(3) Working time limitations due to the nausea resulting from combustion products.

RESULTS

The effect of the electrical field upon the flame and, more particularly, the blow out limit of the flame, was not as pronounced as had been hoped for. This is believed to be due, in part at least, to the lean fuel-air ratios used and the geometrical shape and arrangement of the flameholder. A recommendation for an improved flameholder arrangement will be made in a subsequent section.

The following general statements can be made:

(1) The strength of the electrical field was limited by arcing. At voltages slightly less than that at which arcing occurred, corona could be observed from either or both electrodes.

(2) There was no noticeable effect upon the blow out limit resulting from small changes in the amount of flameholder that protruded from the combustion tube.

(3) Small variations in the distance between the cathode and the anode resulted in no change in the blow out limit.

In order to have a basis of comparison it was decided to have the flameholder tip protrude .5 inch from the mouth of the combustion tube. The plane of the anode

was placed three inches from the tip of the flameholder.

The first anode-cathode configuration used was a 6 inch diameter ring anode and a squared end round cathode flameholder. All sharp edges were slightly rounded. See Fig. 5. This arrangement produced no effect on the flame or blow out limit for fuel-air ratios of .04, .045 or .05 for voltages of from 0 - 13000 volts, d. c.

Data obtained in these runs is tabulated in Table I and plotted in Fig. 8

Blow out values, which remained essentially constant, through the range of electrical field strengths were:

For fuel-air ratio of .04, blow out velocity equalled approximately 25.3 ft/sec.

For fuel-air ratio of .045, blow out velocity equalled approximately 40.6 ft/sec.

For fuel-air ratio of .05, blow out velocity equalled approximately 65 ft/sec.

It was then decided to decrease the size of the ring anode and round the tip of the flameholder. The edges of the ring anode and the flameholder tip were rounded to decrease the likelihood of corona and subsequent arcing. The plane of the anode was located three inches from the tip of the cathode (flameholder) as before.

This, of course, resulted in the cathode and anode being a shorter distance apart than in the first configuration. (See Fig. 6). It was found that the two changes in configuration apparently compensated each other so that corona discharge and arcing occurred at approximately the same voltage values as in the first configuration.

Blow out limits were decreased slightly from the first configuration when no field was applied. This was believed due to the shape of the flameholder tip. As shown in reference 1, a round flameholder tip has a lower blow out limit than a square or concave tip.

Blow out occurred at 25.1 ft/sec for a fuel-air ratio of .04 with no field applied and held this constant value to a field strength of 12000 volts.

When a fuel-air ratio of .045 was used, the no-field blow off limit was 38.9 ft/sec. Again no change was observed in the blow out limit for field strengths that were increased up to 12000 volts. As before, the field strength was limited by arcing.

An increase of fuel-air ratio to .05 increased the no-field blow off limit to 61.1 ft/sec. Increasing the field strength to 12000 volts resulted in an increase of blow out limit of approximately 4 ft/sec or 6.25%. While this result was small it was encouraging in that it was the first indication of an effect of the electric field. See Table II and Fig. 9.

It was decided that although the effect obtained above was small it was a step in the right direction. The ring diameter was effectively decreased to zero or the anode constructed of a 3/8" diameter steel rod bent and located as in Fig. 7. In this case a double cathode was used -- the flameholder and the combustion tube.

The rod was placed in the center of the flame that streamed from the flameholder. The horizontal distance between the flameholder and anode was 3 inches.

The results from this configuration were encouraging but limited by arcing at lower voltages than before. See Table III and Fig. 10.

With a fuel-air ratio of .04, the no-field blow out value was 25.5 ft/sec. The field was increased to the maximum allowable value (limit due to arcing) of 6000 volts, d. c., with a resulting increased value of blow out limit of 1.9 ft/sec or 7.45%.

With a fuel-air ratio of .045, the blow out limit with no field was 39 ft/sec. With an arc-limited field of 6000 volts, d.c., the blow out limit was increased to 42.5 ft/sec, an increase of 9%.

When the fuel-air ratio was increased to .05, the no-field blow out limit was 61.7 ft/sec. With this fuel-air ratio, arcing occurred at voltages greater than 5000 volts, d.c. With this field the blow off limit was 67.1 ft/sec, an increase of 8.75%.

CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation show that the effects of an electric field on a flame and simplified flameholder arrangement are increased best by:

(1) Increasing the fuel/air ratio.

(2) Increasing the field strength.

(3) So placing the electrodes of the field that the effect of the field is to "push" the flame into the fuel supply.

For a lean mixture, the effect of the electrical field on the flameholder flame arrangement is too small to be of commercial value in view of the cost, size, weight and complexity of the apparatus.

However, it is believed that further investigations might profitably be made with rich mixtures and anode-cathode arrangements as shown in Fig. 11.

It is therefore recommended that the investigation be made on stabilization by an electrical field with the ion concentration of the flame increased by the introduction of salts by means of a solution spray into the fuel-air mixture. See Fig. 12.

REFERENCES

Field, J. P., Jr., Theory of the Flameholder, thesis, Rensselaer Polytechnic Institute, 1947.

Polany, M. L. and Markstein, G. H., Project Squid Technical Report No. 5, Phenomena in Electrically and Acoustically Disturbed Bunsen Burner Flames, Cornell Aeronautical Laboratory, Buffalo, N.Y., 1947.

Thomson, J. J., Conduction of Electricity through Gases, Second Edition, University Press, Cambridge England, 1906.

Wilson, H. A., Electrical Conductivity of Flames, Reviews of Modern Physics, 3 1931.

Calcote, H. F., Project Squid Progress Report No. 6, Electrical Properties of Flames, Princeton, New Jersey.

Yarnold, G. D., The Energies of Uniformly Accelerated Particles in a Gas, Philosophical Magazine, 38, 186, 1947.

Anonymous — Fluid Meters-Their Theory and Application, Fourth Edition, A.S.M.E. Publication 1937.

Other books consulted in this investigation but not specifically referred to:

Burk, R. E. and Grummitt, O., — The Chemical Background for Engine Research, Interscience Publishers, Inc., New York, 1943.

Behun, M. A., — Fundamental Investigation of the Effects of Flameholder Temperature on Combustion Stability, Thesis, Rensselaer Polytechnic Institute, 1949.

Friend, J. Newton, — The Chemistry of Combustion, Gurney & Jackson, London, 1922.

Loeb, L. B., — Fundamental Processes of Electrical Discharge in Gases.

Jost, W., — Explosion and Combustion Preceses in Gases, McGraw-Hill Book Company, Inc., New York, 1946.

Lewis, B. and Von Elbe, G., — Combustion, Flames and Explosions of Gases, Cambridge University Press, Cambridge, England, 1938.

Lewis, B., Hottel, H.C., and Nerad, A. J., Third Symposium on Combustion and Flame and Explosion Phenomena, The Williams & Wilkins Company, 1949.

SAMPLE CALCULATIONS

Observed values:

Gas pressure = 111 lbs/in^2

Air temperature = 100^oF

Air pressure = 27.0 inches H_2O

Barometer = 30.13 in. Hg. = 2130 lbs/ft^2

Air differential pressure = 1.2 inches H_2O

Gas differential pressure = .75 inches H_2O

then

$$w_{air} = \frac{lbs}{sec} = .01061 \left[\frac{(2130 + 27x5.2)(1.2)}{560}\right]^{1/2}$$

$$= .01061 \left[\frac{2270x1.2}{560}\right]^{1/2}$$

$$= .01061 \left[4.87\right]^{1/2}$$

$$= .01061x2.21$$

$$= .0235 \text{ lbs/sec}$$

and

$$q_{air} = \frac{ft^3}{sec} = \frac{lbs}{sec} \text{ x } \frac{ft^3}{lbs} = \frac{w}{\rho}$$

$$q_{air} = \frac{wRT}{P}$$

$$= \frac{.0235x53.3x560}{2130}$$

$$= .33 \ ft^3/sec$$

$$w_{gas} = .001 \text{ lbs/sec} \quad \text{(read from curve A3)}$$

$$q_{gas} = \frac{R_{gas}\, w_{gas}\, T}{P}$$

$$= \frac{.001 \times 35 \times 560}{2130}$$

$$= .0092 \text{ ft}^3\text{/sec}$$

then

$$q_{total} = q_{air} + q_{gas}$$

$$= .33 + .0092$$

$$= .3392$$

and

$$\text{exit velocity} = \text{ft/sec} = \frac{\text{ft}^3\text{/sec}}{\text{ft}^2} = \frac{q_{total}}{A}$$

$$\text{Area} = \text{Area tube} - \text{Area flameholder}$$

$$= \frac{\pi D^2_t}{4} - \frac{\pi D^2_{fh}}{4}$$

$$= \frac{\pi}{4}\left[\frac{(1.61)^2}{144} - \frac{.25}{144}\right]$$

$$= \frac{\pi}{4 \times 144}\left[2.592 - .25\right]$$

$$= \frac{\pi \times 2.342}{4 \times 144}$$

$$= .0127 \text{ ft}^2$$

so

$$\text{exit velocity} = \frac{.3392}{.0127} = 26.7 \text{ ft/sec}$$

$$f/a = \frac{\text{wt. fuel}}{\text{wt. air}} = \frac{.001}{.0235} = .0425$$

APPENDIX

AIR FLOW CALIBRATION

From reference 7 the following formula was obtained:

$$w = \frac{\text{lbs}}{\text{sec}} = .0997 \left[\frac{C\ D^2}{(1 - \beta^4)^{.5}}\right] \cdot \left[\rho hw\right]^{1/2}$$

where:

C = coefficient of discharge

D_2 = diameter of orifice in inches

β = diameter of orifice/diameter of pipe

ρ = density in lbs/ft^3

hw = differential pressure across orifice in inches of water

Coefficient of discharge, C, is a function of Reynolds number, pipe diameter and orifice diameter.

$$\text{Reynolds Number} = \frac{\rho V l}{\mu}$$

$$= \frac{P}{gRT} \cdot \frac{Vl}{\mu}$$

where:

P = pressure in lbs/ft^2

$= 2116 + 26.5 \times 5.204$

$= 2116 + 138$

$= 2254$ lbs/ft^2

$g = 32.2$ ft/sec^2

$R = 53.3$ ft/degree

$T = 560$ degrees Rankine

l = pipe diameter

= 3.068 inches

= .256 feet

$\mu = 3.723 \times 10^{-7}$ slugs/ft sec

Then

$$\text{Reynolds Number} = \frac{(2254)(.256)(V)}{(32.2)(53.3)(560)(3.723 \times 10^{-7})}$$

$$= 1.61 \times 10^{3}\ V$$

and

$$V = \frac{ft}{sec} = \frac{Q}{Area} = \frac{ft^3/sec}{ft^2}$$

so

$$V = \frac{Q}{\frac{\pi D^2}{4}}$$

$$V = \frac{Q}{\frac{\pi (.256)^2}{4}} = \frac{Q}{.0515}$$

so

$$\text{Reynolds Number} = 1.61 \times 10^{3}\ \frac{Q}{.0515}$$

$$= 31250\ Q$$

Then from Fig. 25(a) of reference 7 and Table AI the average value of coefficient of discharge was found to be:

$$C = .609$$

$$\beta = \frac{1.12}{3.068}$$

$$= .365$$

$$\rho = \frac{P}{RT}$$

$$= \frac{P}{53.3T}$$

then

$$w = \frac{(.0997)(.609)(1.12)^2}{[1 - (.365)^4]^{.5}} \left[\frac{P \quad hw}{53.3T}\right]^{1/2}$$

$$= .01061 \left[\frac{Phw}{T}\right]^{1/2}$$

where

$P = 433$ inches H_2O

$T = 560^{\circ}$ R

$w = .0213 \quad hw$

The above relation of weight flow and pressure differential across the orifice is obtained by maintaining the air static pressure constant at 26.5 inches of water gage and the air temperature constant at 100°F.

Thus a plot can be made of what differential pressure to set by means of the gate valve in order to obtain any desired weight flow. Computations to accomplish this are carried out in Table AII and the results plotted on Figs. A1 and A2.

TABLE A I

COMPUTATION OF DISCHARGE COEFFICIENT

Q	Reynolds Number	β	Discharge Coefficient
ft^3/sec	-	-	-
1	31250	.373	.614
2	62500		.610
3	93750		.609
4	125000		.6085
5	156250		.608
6	187500		.6075
7	219000		.607

Average = .609

TABLE A II

COMPUTATION OF AIR WEIGHT

FLOW CURVE

hw inches H_2O	$\sqrt{hw}$ in. H_2O	w lbs air/sec
.5	.780	.01544
1.0	1	.0218
1.5	1.225	.02672
2.0	1.414	.03083
2.5	1.58	.03442
3.0	1.734	.0378
3.5	1.872	.0408
4.0	2.0	.0436
4.5	2.122	.0463
5.0	2.24	.0488
5.5	2.345	.0511
6.0	2.452	.0535
6.5	2.55	.0556
7.0	2.647	.0577
7.5	2.74	.0597
8.0	2.83	.0617

8.5	2.92	.0637
9.0	3.0	.0654
9.5	3.082	.0672
10.0	3.165	.069
10.5	3.242	.0707
11.0	3.32	.0724
11.5	3.395	.074
12.0	3.47	.0757
12.5	3.54	.0772
13.0	3.61	.0787
13.5	3.68	.08025
14.0	3.745	.0817
14.5	3.815	.0831
15.0	3.88	.0846
15.55	3.94	.0859
16.0	4.00	.0872

FUEL FLOW CALIBRATION

Since an orifice was made to measure the fuel flow, it was necessary that a calibration be made.

This was done by placing a tank of the fuel upon scales and measuring the length of time required to burn a portion of the fuel, either .25 or .5 lb. Pressure was maintained constant in the tank by means of heat applied with a blowtorch.

Values obtained in this calibration are listed in Table A III and the data are plotted as Fig. A 3.

This curve shows the weight of fuel in pounds per second that will flow through the orifice when the corresponding differential pressure is held across the orifice and 110 lbs/in^2 gage is the gas static pressure.

TABLE A III

CALIBRATION OF FUEL ORIFICE

P inches H_2O	W lbs	t minutes	Fuel Flow lbs/second
.4	.25	5.983	.000696
.4		4.386	.000951
.8		4.042	.001031
1.0		4.175	.001161
1.2		3.412	.001221
1.4		3.120	.001336
1.6		2.769	.001507
1.8		2.567	.001622
2.0		2.510	.001660
3.0		2.083	.00200
4.0		1.945	.00214
5.0		1.629	.00256
6.0		1.518	.002741
7.0	.5	2.592	.003213
8.0		2.413	.00345
9.0		2.308	.00361
10.0		2.250	.00370
11.0		2.142	.003883
12.1		2.042	.004075

13.1	.5	1.958	.00426
15		1.877	.00445
17		1.774	.00469
19		1.587	.00525

TABLE A IV

Data for Computation of Curves of constant fuel/air ratio.

For Fuel/Air = .05:

fuel lbs/sec	air lbs/sec	fuel P in. H_2O	air P in. H_2O
.0005	.01	.15	.25
.0008	.016	.475	.5025
.0011	.022	.9	1.0
.0014	.028	1.4	1.65
.0017	.034	2.1	2.45
.0020	.04	3.0	3.4
.0023	.046	4.2	4.45
.0026	.052	5.3	5.65
.0029	.058	6.3	7.1
.0032	.064	7.4	8.8
.0035	.07	8.6	10.3
.0038	.076	10.45	12.05
.0041	.082	12.15	-

For Fuel/Air = .045:

fuel lbs/sec	air lbs/sec	fuel P in. H_2O	air P in. H_2O
.0005	.0111	.15	.252
.0008	.01778	.475	.65
.0011	.0244	.9	1.225
.0014	.0311	1.4	2.025
.0017	.0378	2.1	3.060
.0020	.0444	3.0	3.725
.0023	.0511	4.2	5.475
.0026	.05775	5.3	7.05
.0029	.0645	6.3	8.775
.0032	.0711	7.4	10.675
.0035	.0778	8.6	12.6
.0038	.0845	10.45	
.0041	.0911	12.15	

For Fuel/Air = .04:

fuel lbs/sec	air lbs/sec	fuel P in H_2O	air P in H_2O
.0005	.0125	.15	.33
.0008	.020	.475	.81
.0011	.0275	.9	1.575
.0014	.035	1.4	2.625
.0017	.0425	2.1	3.83
.0020	.05	3.0	5.225
.0023	.0575	4.2	6.950
.0026	.065	5.3	8.9
.0029	.0725	6.3	11.1
.0032	.080	7.4	13.35
.0035	.0875	8.6	
.0038	.095	10.45	
.0041	.1025	12.15	

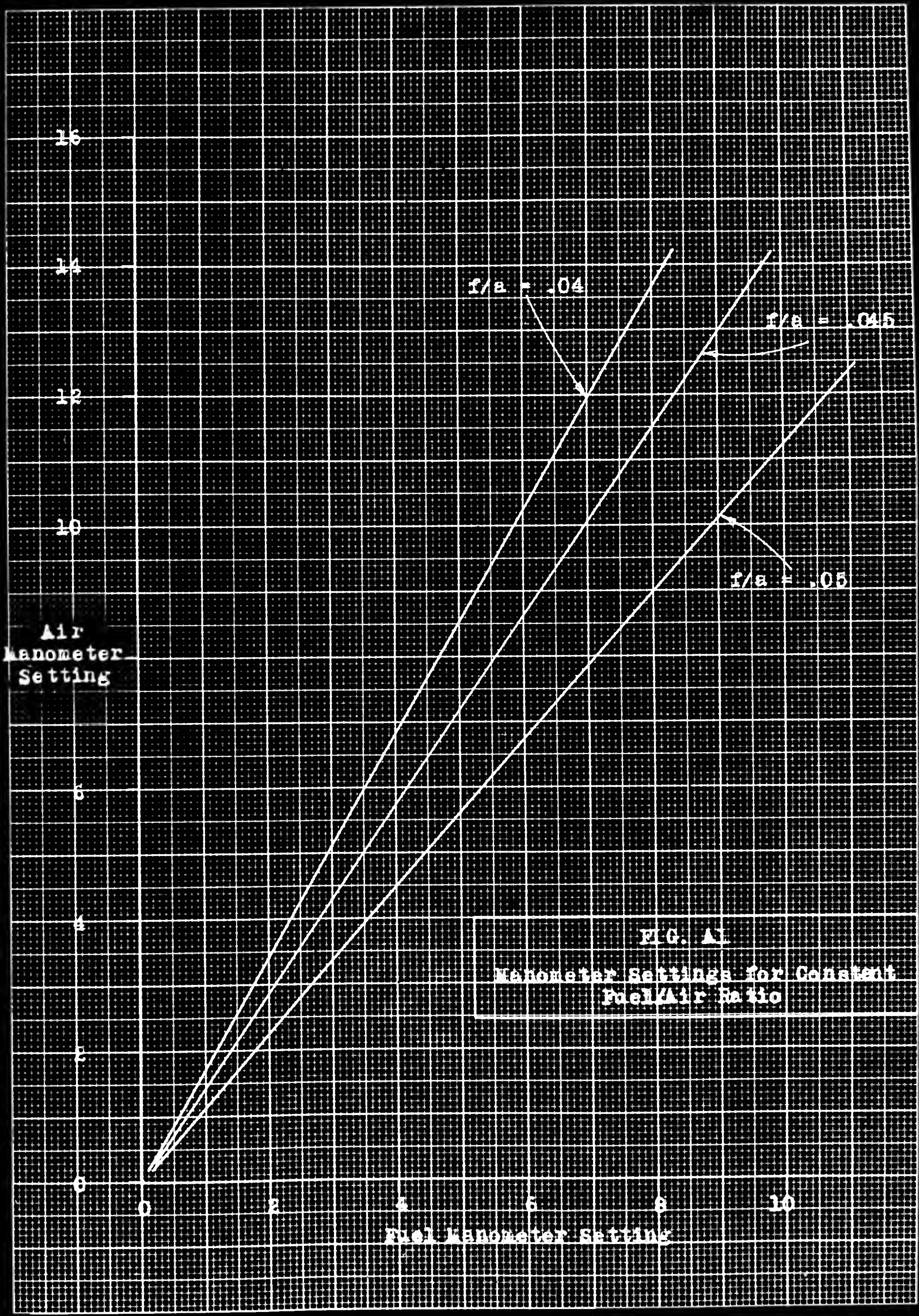


FIG. A1

Manometer Settings for Constant Fuel/Air Ratio

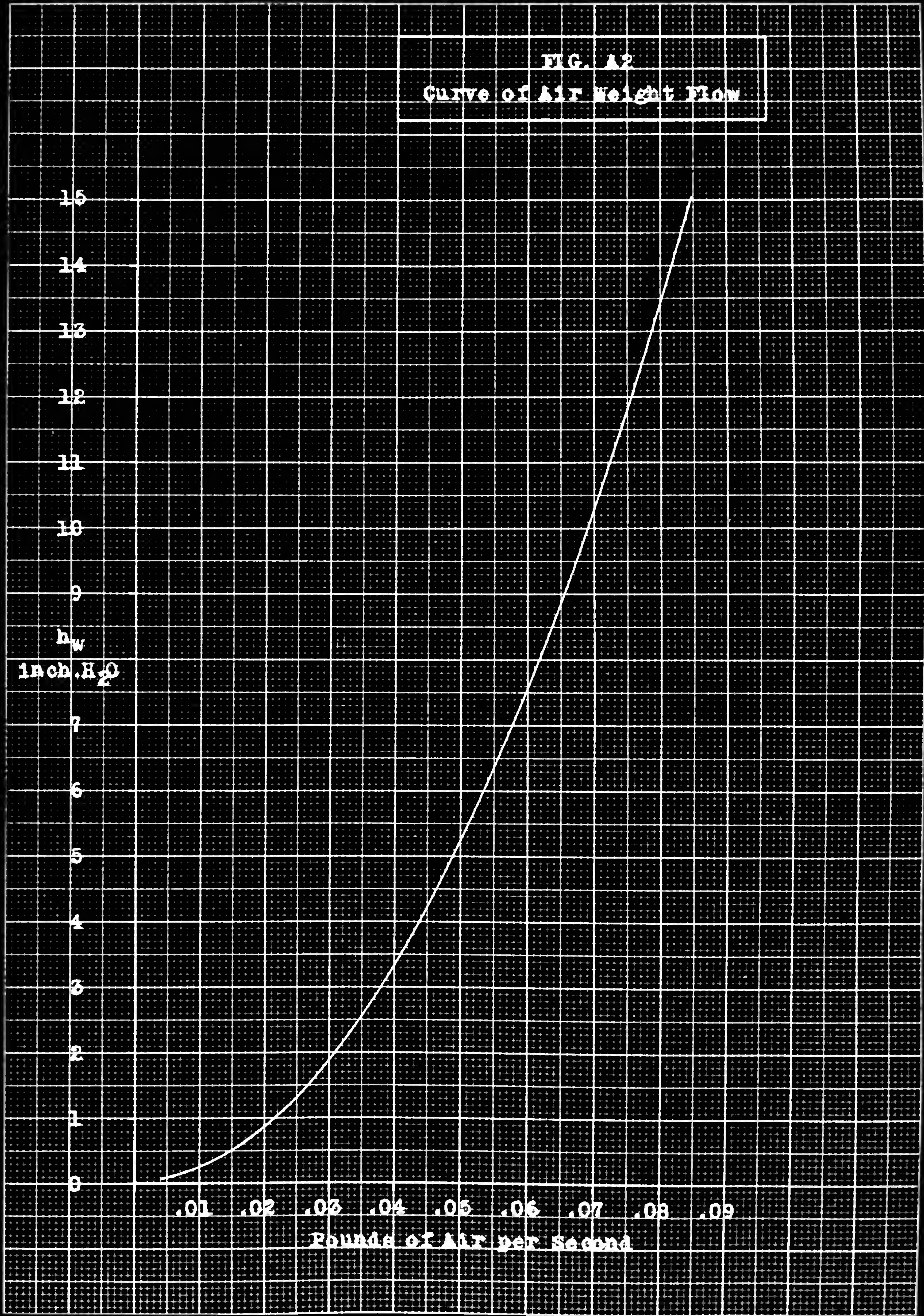


FIG. A2
Curve of Air Weight Flow
15
14
13
12
11
10
9
h_w
inch. H_2O
7
6
5
4
3
2
1
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
Pounds of Air per Second

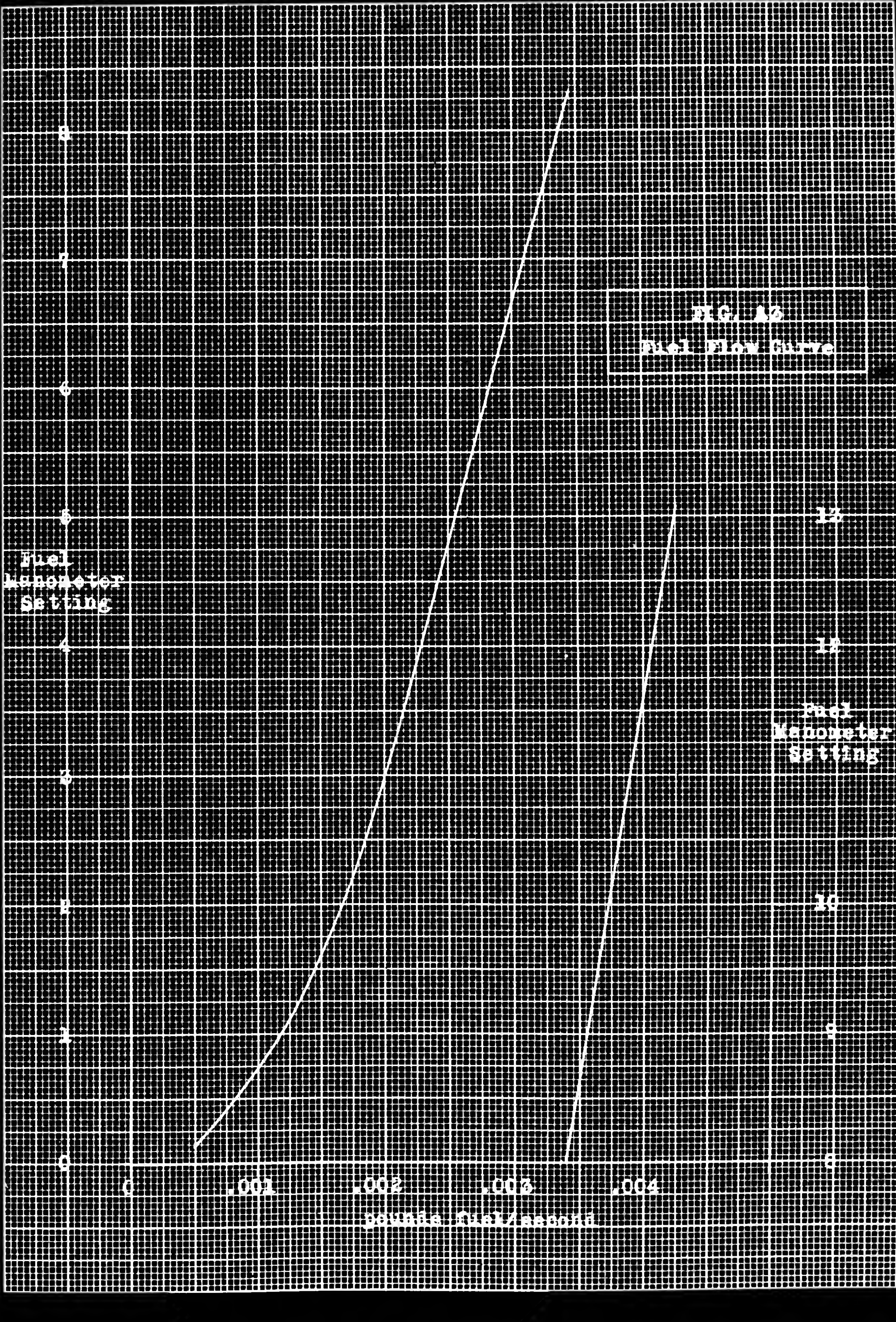


FIG. A3
Fuel Flow Curve
Fuel Manometer Setting
Fuel Manometer Setting
pounds fuel/second
0
.001
.002
.003
.004
0
1
2
3
4
5
6
7
8
9
10
12
13

Potential	Gas Pres.	Air Temp.	Air Pres.	h_{air}	W_{air}	Q_{air}	h_{gas}	W_{gas}	Q_{gas}	F/A	Q_{total}	Velocity
volts	$\frac{lbs}{in^2}$	^oF	in.H_2O	in.H_2O	$\frac{lbs}{in^2}$	$\frac{ft^3}{sec}$	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	-	$\frac{ft^3}{sec}$	$\frac{ft}{sec}$
0	112	99	27.2	1.20	.02365	.331	.7	.000975	.00896	.0412	.340	26.1
2000	110	99	27.0	1.25	.0239	.3345	.65	.00095	.00872	.0397	.343	26.8
4000	111	100	27.3	1.10	.0227	.3180	.65	.00095	.00874	.0418	.327	25.6
6000	103	101	27.2	1.00	.0217	.304	.60	.0009	.0083	.0414	.312	24.4
8000	110	98	26.8	1.20	.02365	.330	.60	.0009	.00821	.0380	.438	26.4
10000	109	99	26.8	1.00	.0211	.296	.60	.0009	.00836	.0413	.304	23.8
12000	111	100	27.0	1.20	.0236	.332	.75	.001	.0092	.0422	.341	26.8
0	111	98	27	2.90	.0365	.509	2.0	.00167	.0153	.0458	.524	41.0
2000	111	99	26.7	2.80	.0358	.502	1.8	.0016	.0147	.0446	.517	40.4
4000	109	100	26.8	3.10	.0375	.525	1.9	.00165	.0152	.044	.540	42.2
6000	109	102	27.2	3.00	.0368	.517	2.1	.00165	.0152	.044	.532	41.7
8000	110	96	26.9	2.70	.0352	.485	1.8	.00157	.01435	.0452	.499	39.1
10000	113	99	26.8	2.60	.0345	.482	1.8	.0016	.0147	.0463	.4967	38.1
12000	110	102	27.0	3.00	.0372	.522	2.0	.00167	.0154	.0448	.537	42.0

TABLE I Observed and Computed Data for 6 inch Diameter Ring Anode and Square End Flameholder Cathode.

Potential volts	Gas Pres. $\frac{lbs}{in^2}$	Air Temp. ^oF	Air Pres. in.H_2O	h_{air} in.H_2O	W_{air} $\frac{lbs}{in^2}$	Q_{air} $\frac{ft^3}{sec}$	h_{gas} in.H_2O	W_{gas} $\frac{lbs}{sec}$	Q_{gas} $\frac{ft^3}{sec}$	F/A -	Q_{total} $\frac{ft^3}{sec}$	Velocity $\frac{ft}{sec}$
0	110	100	27	7.10	.057	.798	6.2	.00287	.0264	.05	.818	64.0
2000	111	102	27	7.40	.058	.815	6.2	.00287	.0265	.0495	.8415	65.8
4000	109	98	27	7.00	.0565	.790	6.2	.00287	.0263	.0508	.8163	63.9
6000	112	100	26.9	7.10	.057	.800	6.5	.00292	.0269	.0512	.8269	64.7
8000	110	101	27.1	7.15	.057	.801	6.2	.00288	.0265	.0505	.8275	64.7
10000	109	102	27.0	7.50	.0585	.823	6.2	.00287	.0264	.0491	.8494	66.4
12000	110	99	27.1	7.50	.0585	.819	6.6	.00299	.0274	.0511	.8464	64.3

TABLE I (cont.)

Potential	Gas Pres.	Air Temp.	Air Pres.	h_{air}	W_{air}	Q_{air}	h_{gas}	W_{gas}	Q_{gas}	F/A	Q_{total}	Velocity
volts	$\frac{lbs}{in^2}$	°F	in.H_2O	in.H_2O	$\frac{lbs}{in^2}$	$\frac{ft^3}{sec}$	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	-	$\frac{ft^3}{sec}$	$\frac{ft}{sec}$
0	112	98	27	1.10	.0222	.313	.6	.0009	.00834	.0405	.321	25.1
2000	112	99	26.7	1.35	.0247	.348	.7	.000975	.00904	.0394	.357	28.0
4000	110	101	27.1	1.20	.0234	.332	.65	.00093	.00864	.0397	.331	26.9
6000	109	97	27.0	1.10	.0226	.318	.65	.00093	.0086	.0411	.327	25.6
8000	110	99	26.9	1.20	.023	.3255	.6	.0009	.00835	.0391	.334	26.1
10000	110	100	27.0	1.10	.022	.311	.6	.0009	.00836	.0409	.319	25.1
12000	110	102	27.2	1.15	.0229	.325	.65	.00093	.00865	.0406	.334	26.1
0	111	98	27.2	2.65	.0348	.484	1.75	.00156	.01422	.0448	.498	38.9
2000	111	100	26.9	2.60	.0346	.482	1.80	.00158	.0145	.0457	.497	38.9
4000	110	103	27.0	2.55	.0340	.477	1.90	.00162	.0149	.0476	.492	38.5
6000	111	99	27.2	2.45	.0335	.466	1.80	.00158	.0144	.0471	.480	37.5
8000	112	101	27.1	2.35	.0328	.459	1.60	.0015	.0138	.0457	.473	37.0
10000	108	98	27.2	2.45	.0334	.465	1.70	.00155	.0142	.0464	.479	37.4
12000	109	100	26.9	2.80	.0359	.501	1.80	.00158	.0145	.0440	.5155	39.6

TABLE II Computed and Observed Data for 3 inch Diameter Ring Anode and Round End Flameholder Cathode.

Potential	Gas Pres.	Air Temp.	Air Pres.	h_{air}	W_{air}	Q_{air}	h_{gas}	W_{gas}	Q_{gas}	F/A	Q_{total}	Velocity
Volts	$\frac{lbs}{in^2}$	°F	in.H_2O	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	-	$\frac{ft^3}{sec}$	$\frac{ft}{sec}$
0	112	99	27.1	6.50			6.0					
	108	100	26.9	6.50			6.0					
	110	99.5	27.0	6.50	.0544	.756	6.0	.00281	.02565	.0517	.782	61.1
2000	110	100	26.9	6.20			5.4					
	110	100	26.9	6.30			5.6					
	110	100	26.9	6.25	.0535	.746	5.5	.00267	.02445	.0499	.771	60.4
4000	112	101	26.9	7.00			6.0					
	110	103	27.1	7.00			6.0					
	111	102	27.0	7.00	.0565	.792	6.0	.00281	.0256	.0497	.818	64.0
6000	111	98	27.0	6.70			6.0					
	109	98	27.0	6.70			6.0					
	110	98	27.0	6.70	.0555	.771	6.0	.00281	.0256	.0506	.797	62.4
8000	109	98	26.8	7.00			6.2					
	109	100	26.8	7.00			6.4					
	109	99	26.8	7.00	.0565	.790	6.3	.00290	.0266	.0513	.817	64.0

TABLE II (cont.)

Potential	Gas Pres.	Air Temp.	Air Pres.	h_{air}	W_{air}	Q_{air}	h_{gas}	W_{gas}	Q_{gas}	F/A	Q_{total}	Velocity
volts	$\frac{lbs}{in^2}$	^oF	in.H_2O	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	-	$\frac{ft^3}{sec}$	$\frac{ft}{sec}$
10000	109	100	26.8	7.40			6.3					
	107	102	27.2	7.30			6.3					
	108	101	27.0	7.35	.0578	.810	6.3	.0029	.0266	.0501	.837	65.5
12000	113	102	27.2	7.25			6.1					
	111	103	27.1	7.30			6.3					
	112	102.5	27.15	7.27	.0575	.805	6.2	.00287	.0264	.0499	.831	65.0

TABLE II (cont.)

Potential	Gas Pres.	Air Temp.	Air Pres.	h_{air}	W_{air}	Q_{air}	h_{gas}	W_{gas}	Q_{gas}	F/A	Q_{total}	Velocity
Volts	$\frac{lbs}{in^2}$	°F	in.H_2O	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	-	$\frac{ft^3}{sec}$	$\frac{ft}{sec}$
0	110	97	27.0	1.10	.0225	.318	.6	.0009	.00836	.0399	.326	25.5
1000	111	98	27.0	1.20	.0234	.331	.65	.00093	.00865	.0397	.340	26.6
2000	112	100	27.1	1.20	.0230	.327	.65	.00093	.00868	.0404	.336	26.3
3000	113	102	27.2	1.10	.0224	.320	.6	.0009	.00844	.0402	.328	25.6
4000	112	99	27.0	1.20	.0230	.327	.6	.0009	.0084	.0391	.335	26.2
5000	110	101	27.0	1.20	.0234	.333	.625	.00092	.0086	.0393	.342	26.8
6000	110	102	26.8	1.30	.0239	.341	.65	.00093	.0087	.0389	.350	27.4
0	110	98	27.2	2.60	.0342	.484	1.8	.00158	.01472	.0462	.499	39.0
1000	110	99	27.2	2.53	.0338	.480	1.85	.00160	.0149	.0474	.499	39.0
2000	109	101	26.9	2.63	.0344	.490	1.8	.00158	.0148	.0460	.505	39.5
3000	108	100	27.0	3.00	.0368	.524	1.9	.00162	.0151	.0440	.539	42.1
4000	111	101	27.0	2.95	.0364	.519	1.9	.00162	.01515	.0445	.534	41.7
5000	110	98	27.1	3.00	.0367	.521	1.9	.00162	.0151	.0442	.536	42.1
6000	112	100	27.1	3.05	.0370	.525	1.95	.00165	.0182	.0446	.543	42.5

TABLE III

Observed and Computed Data for Round End Rod Anode and Round End Flameholder and Combustion Tube Cathode

Potential	Gas Pres.	Air Temp.	Air Pres.	h_{air}	W_{air}	Q_{air}	h_{gas}	W_{gas}	Q_{gas}	F/A	Q_{total}	Velocity
Volts	$\frac{lbs}{in^2}$	°F	in.H_2O	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	in.H_2O	$\frac{lbs}{sec}$	$\frac{ft^3}{sec}$	-	$\frac{ft^3}{sec}$	$\frac{ft}{sec}$
0	111	100	27.0	6.60			5.8					
	113	100	27.0	6.60			5.8					
	112	100	27.0	6.60	.055	.764	5.8	.00275	.0251	.05	.789	61.7
1000	109	101	26.8	6.75			5.8					
	109	103	26.8	6.70			5.8					
	109	102	26.8	6.73	.0555	.772	5.8	.00275	.0252	.0496	.797	62.4
2000	110	98	26.8	6.55			5.9					
	107	100	26.9	6.45			5.9					
	108.5	99	26.9	6.50	.0547	.756	5.9	.00277	.0252	.0506	.781	61.1
3000	108	99	27.0	7.15			5.9					
	108	101	27.2	7.20			6.1					
	108	100	27.1	7.18	.0594	.798	6.0	.00281	.0256	.049	.824	64.4
4000	111	102	26.8	7.15			6.3					
	109	102	26.8	7.20			6.1					
	110	102	26.8	7.18	.0580	.808	6.2	.00288	.0264	.0497	.834	65.2
5000	108	100	27.0	7.8			6.5					
	110	99	27.2	7.8			6.5					
	109	99.5	27.1	7.80	.0598	.830	6.5	.00295	.0269	.0493	.857	67.1

TABLE III (cont.)

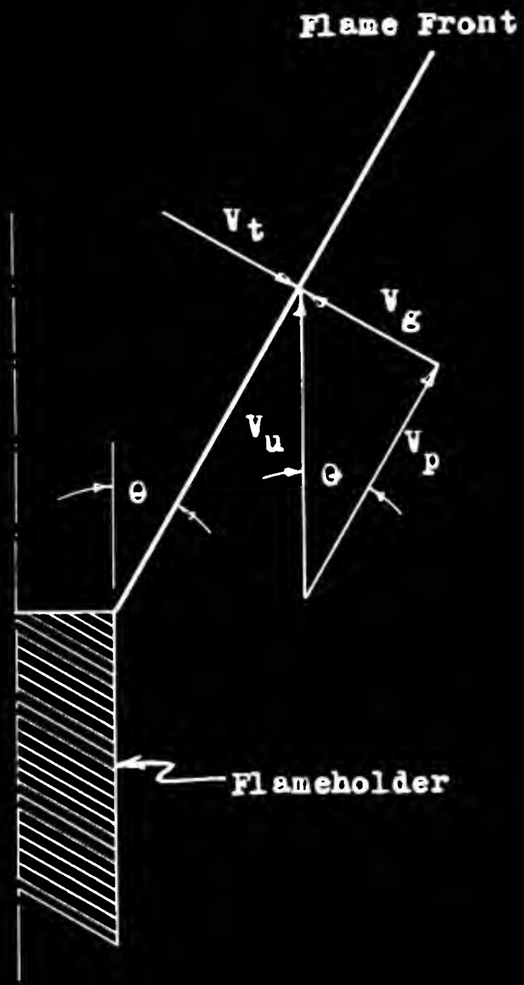
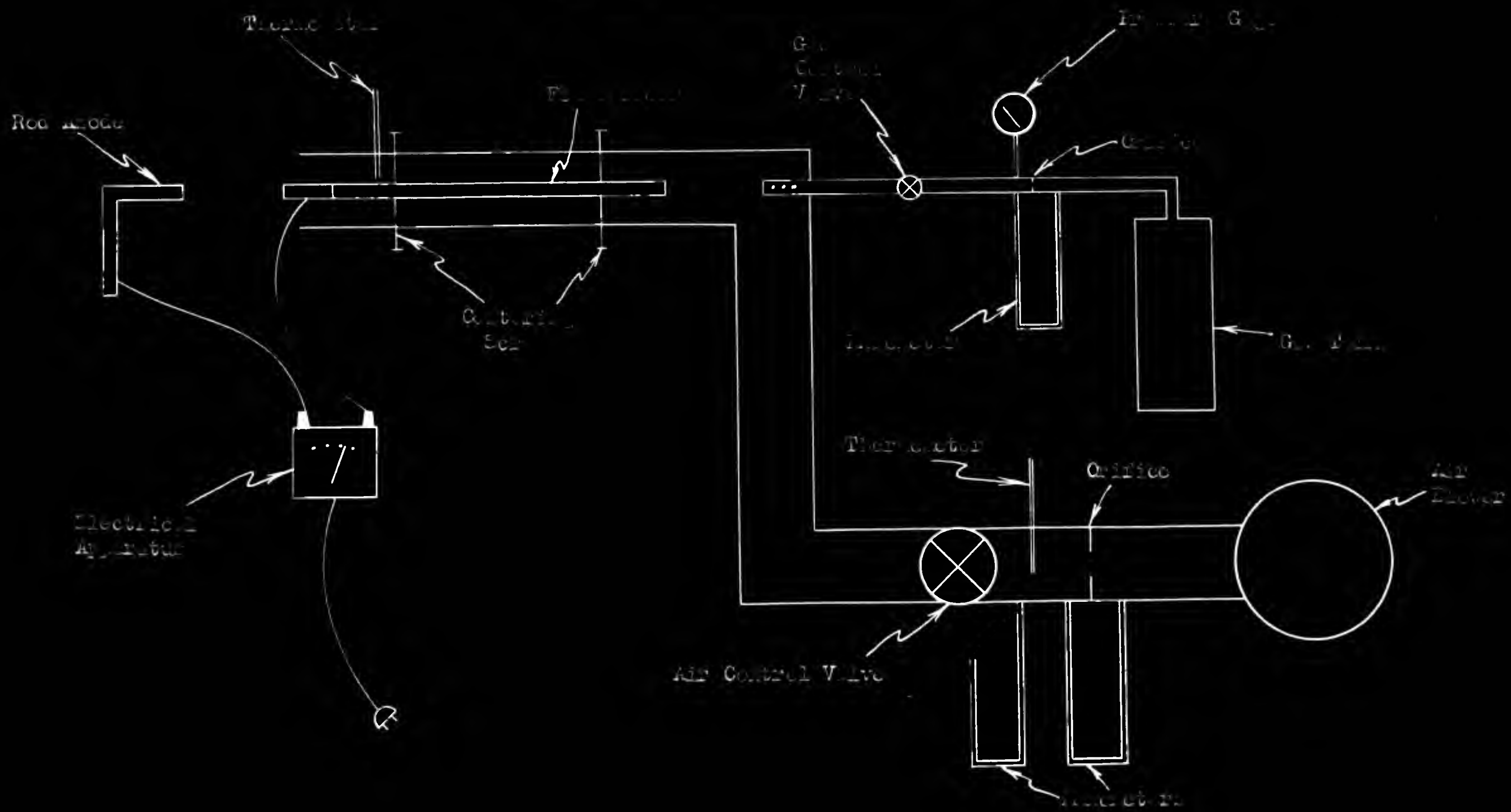


FIG. 1

Sketch of Flame Front



Rod Anode
Electrical Apparatus
Orifice
Air Control Valve

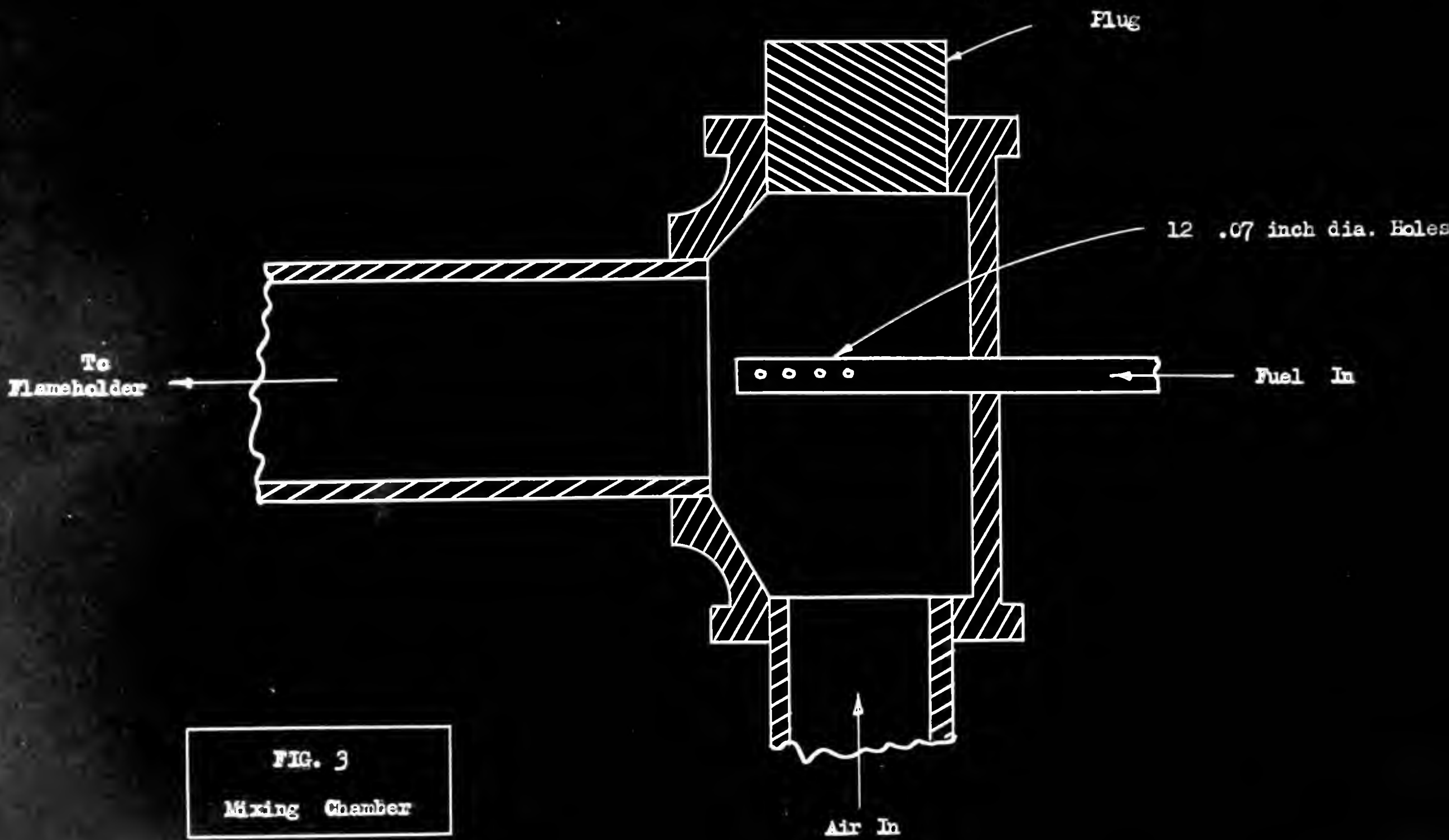


FIG. 3

Mixing Chamber

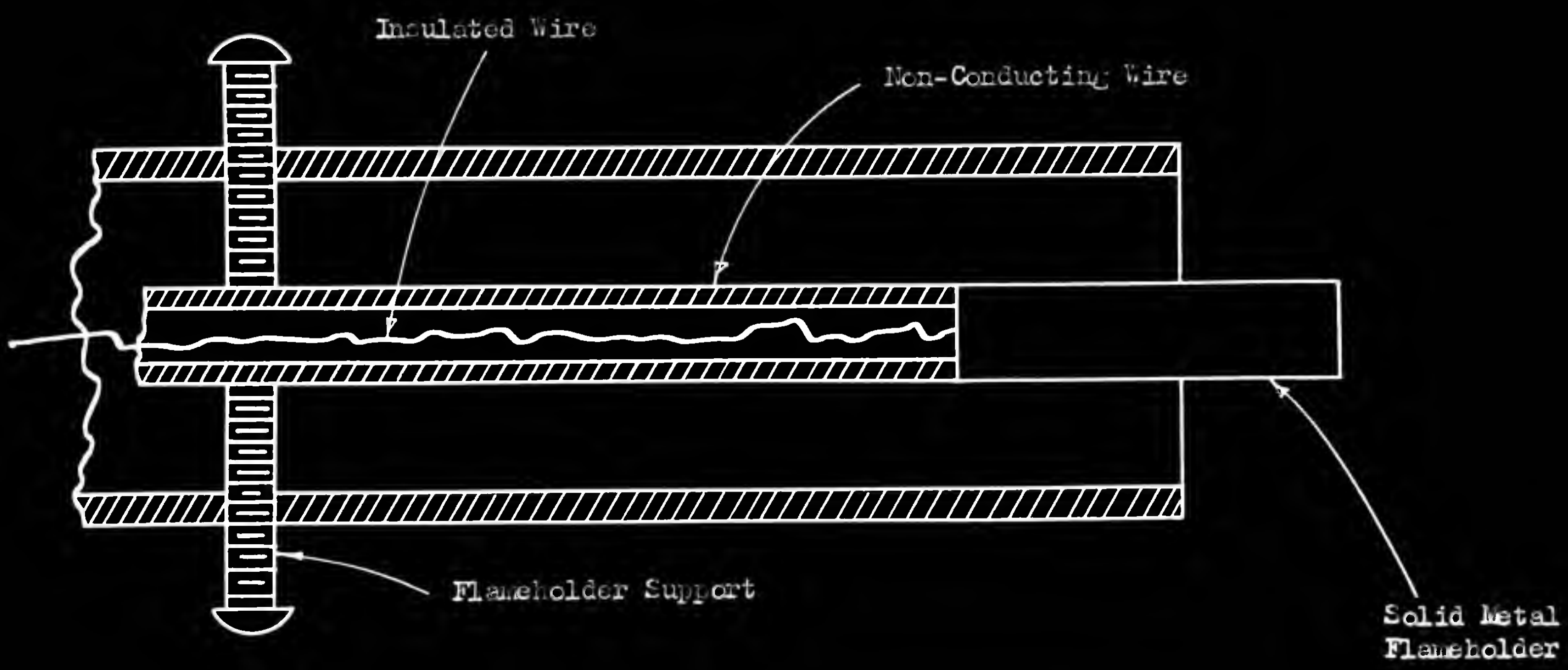
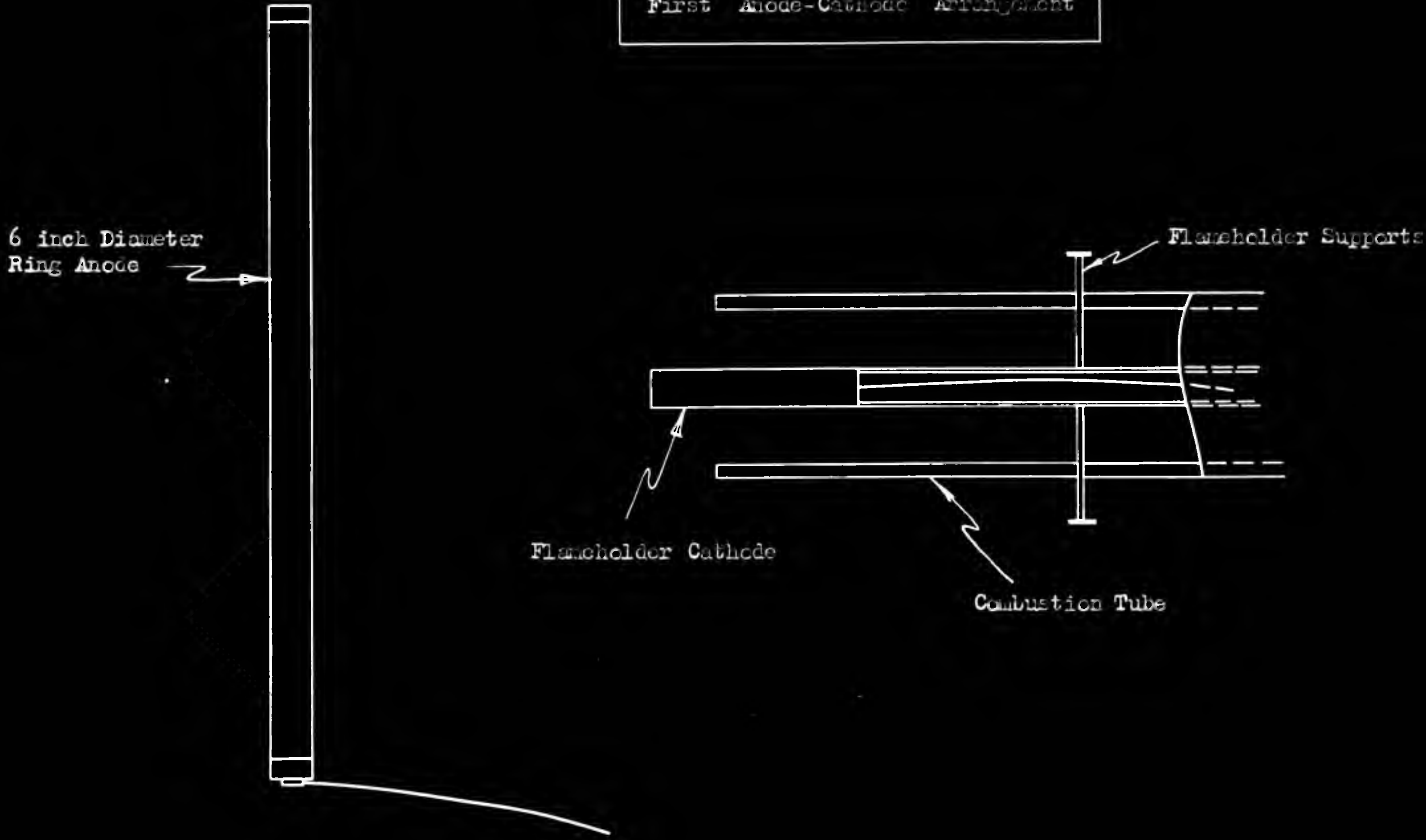


FIG. 4

Sketch of Flameholder

FIG. 5

First Anode-Cathode Arrangement



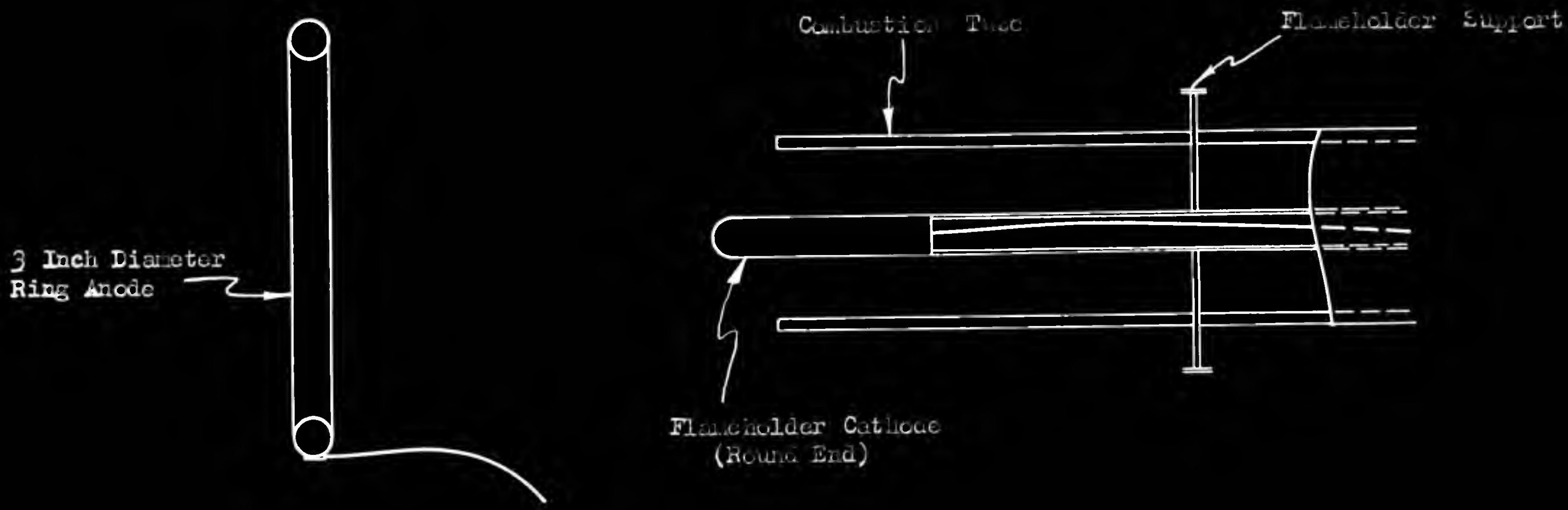
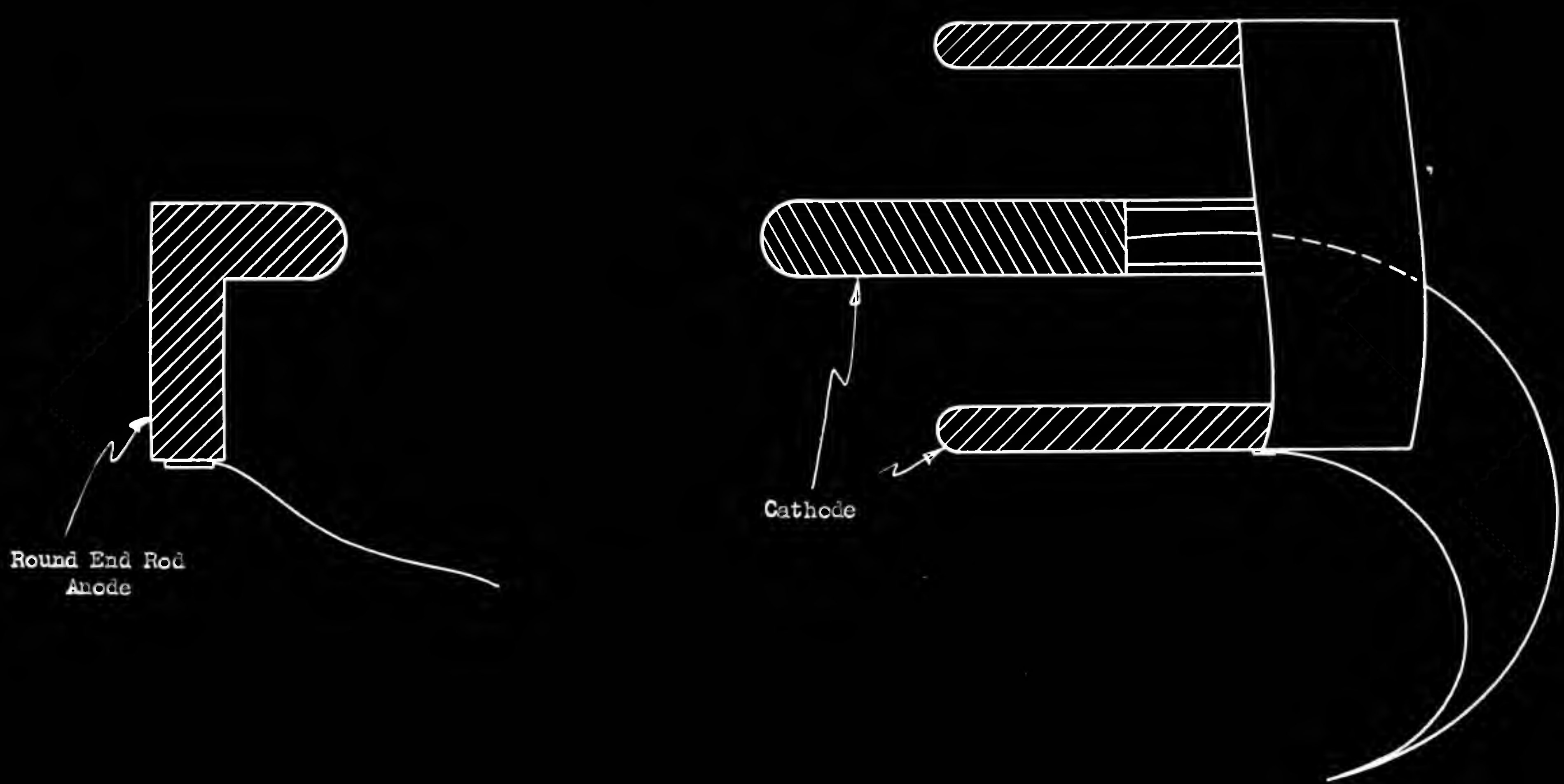


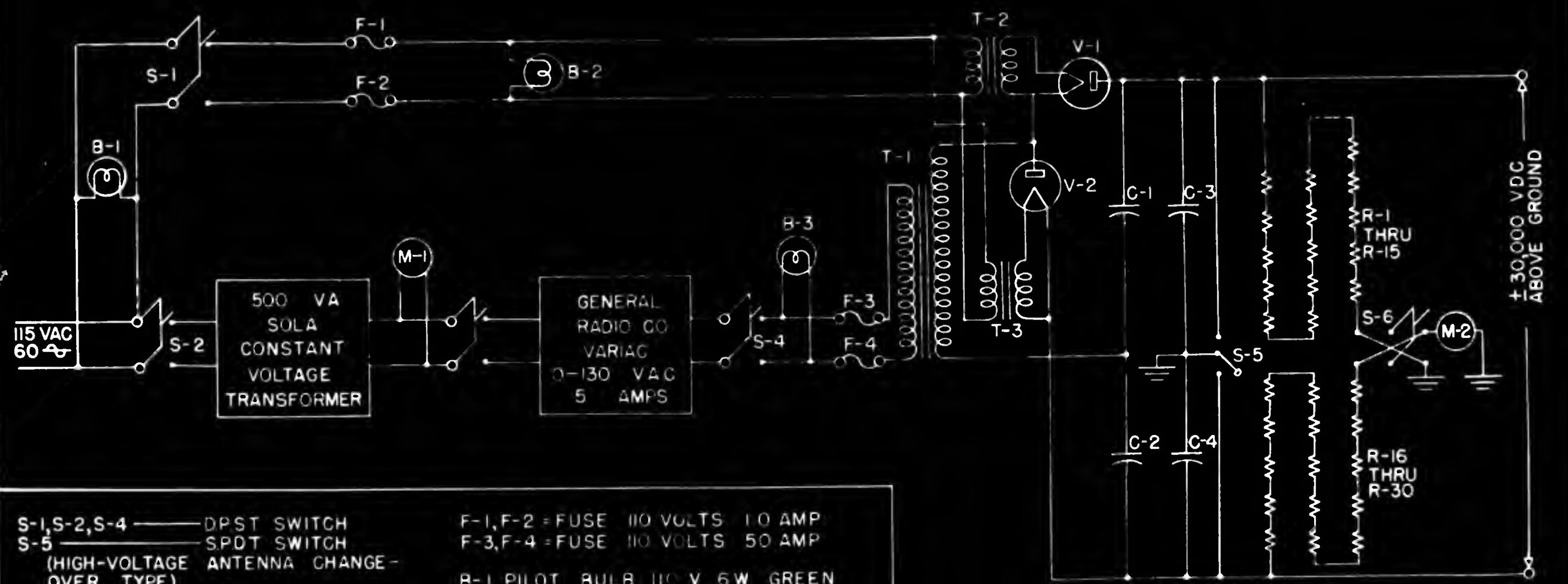
FIG. 6

Second Anode-Cathode Arrangement

FIG. 7

Third Anode-Cathode Arrangement





S-1,S-2,S-4 ——— DPST SWITCH
S-5 ——— SPDT SWITCH
(HIGH-VOLTAGE ANTENNA CHANGE-OVER TYPE)
S-6 ——— DPDT SWITCH
M-1 ——— 0-250 VAC
M-2 ——— 0-10 MA. D.C.
SCALE: 0-30 KVDC

T-1 = HIGH VOLTAGE TRANSFORMER
PRIMARY: 0-110 VAC
SECONDARY: 0-10,000 VOLTS (RMS)
70 MILLAMPERES
T-2,T-3 = 110 V. 60 ~ PRIMARY
5.3 V. AT 6.0 AMP. SECONDARY
35 KV. TEST INSUL. AMERTRAN

F-1,F-2 = FUSE 110 VOLTS 1.0 AMP
F-3,F-4 = FUSE 110 VOLTS 5.0 AMP

B-1 PILOT BULB 110 V 6W GREEN
B-2 PILOT BULB 110 V 6W AMBER
B-3 PILOT BULB 110 V 6W RED

V-1,V-2 HI-VACUM RECTIFIER #8020
(ELECTRONIC ENTERPRIZES INC NJ)

C-1,C-2,C-3,C-4 ——— 0.25 MICROFARAD
27,000 VDC WORKING
OIL-FILLED CONDENSER

R-1 THROUGH R-30 RESISTORS
2 WATTS 2 MEGOHM

FIG. 8

Diagram of Electrical Apparatus

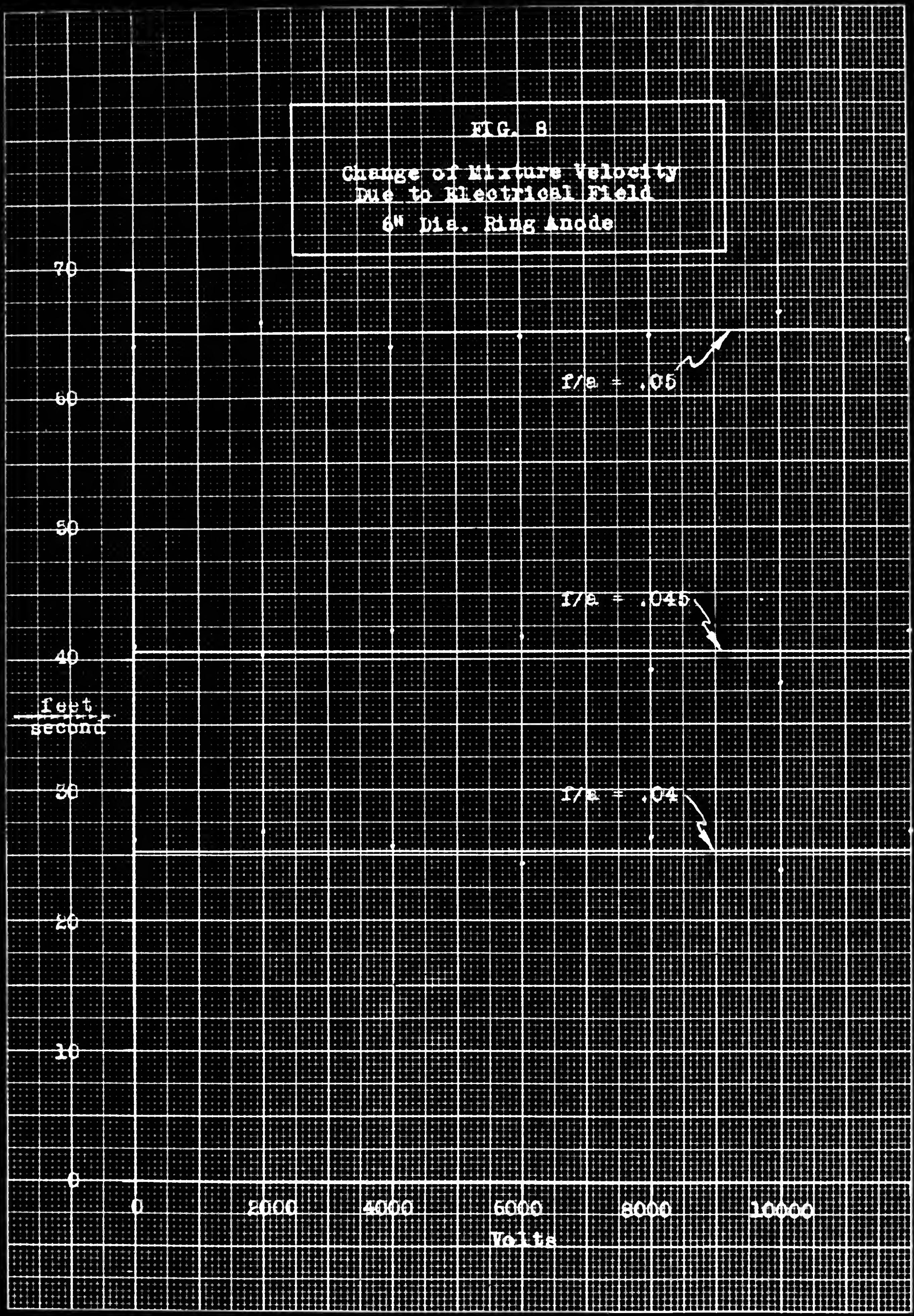


FIG. 8
Change of Mixture Velocity
Due to Electrical Field
6" Dia. Ring Anode
f/a = .05
f/a = .045
f/a = .04
70
60
50
40
30
20
10
0
feet/second
0
2000
4000
6000
8000
10000
Volts

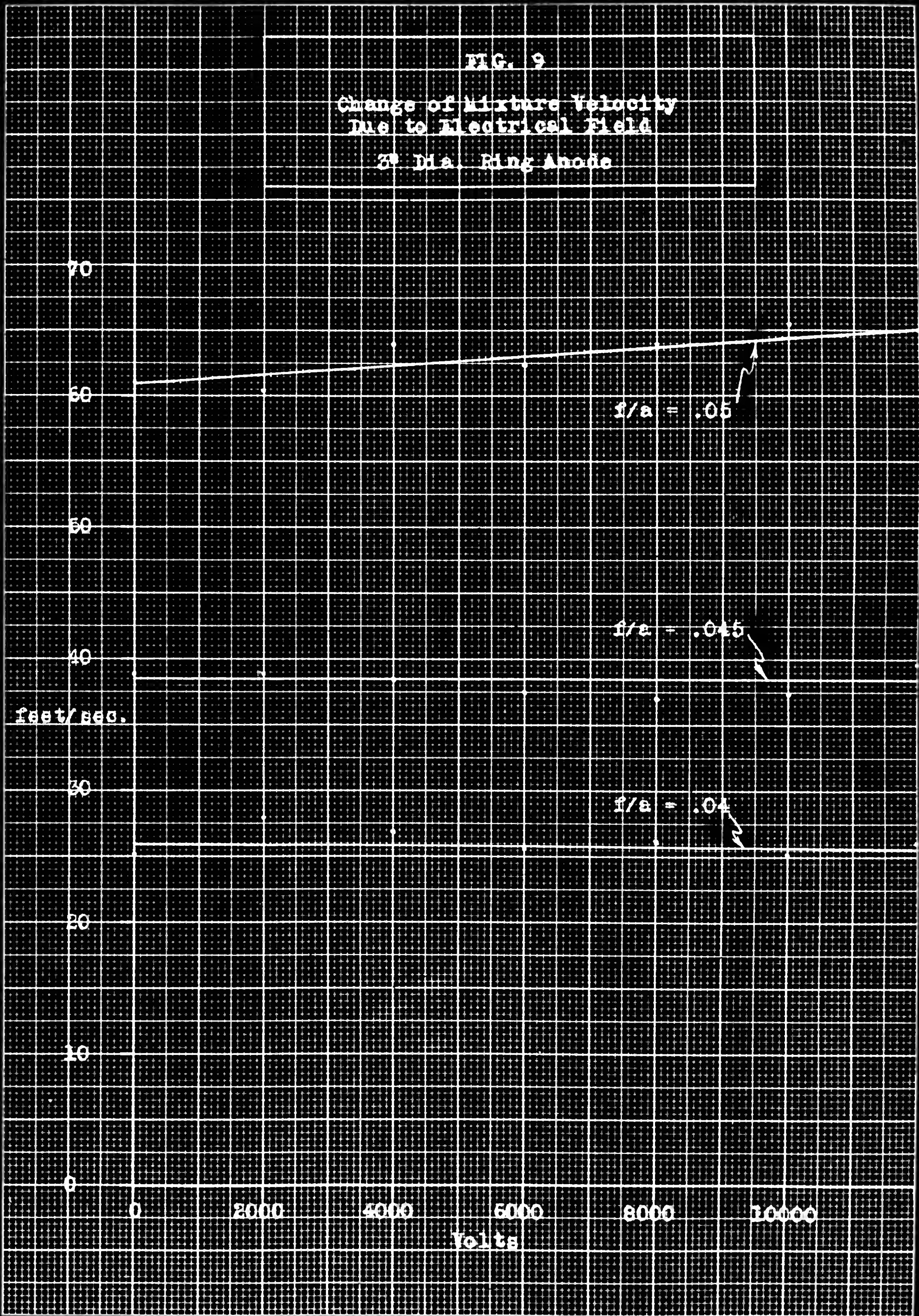


FIG. 9
Change of Mixture Velocity
Due to Electrical Field
3" Dia. Ring Anode
70
60
50
40
30
20
10
0
feet/sec.
f/a = .05
f/a = .045
f/a = .04
0
2000
4000
6000
8000
10000
Volts

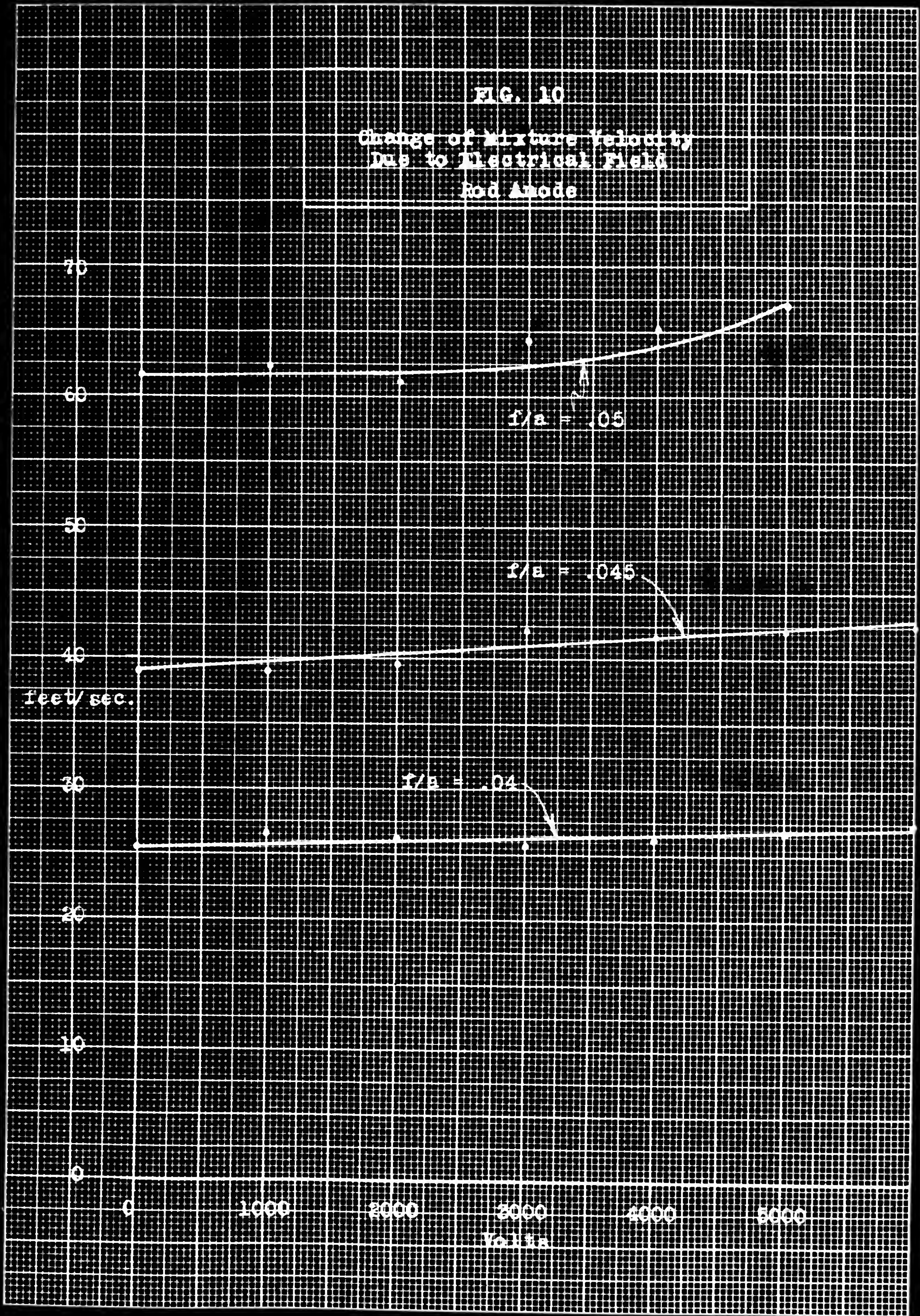


FIG. 10

Change of Mixture Velocity
Due to Electrical Field
Rod Anode

FIG. 11

SUGGESTED CHANGE IN CATHODE SHAPE

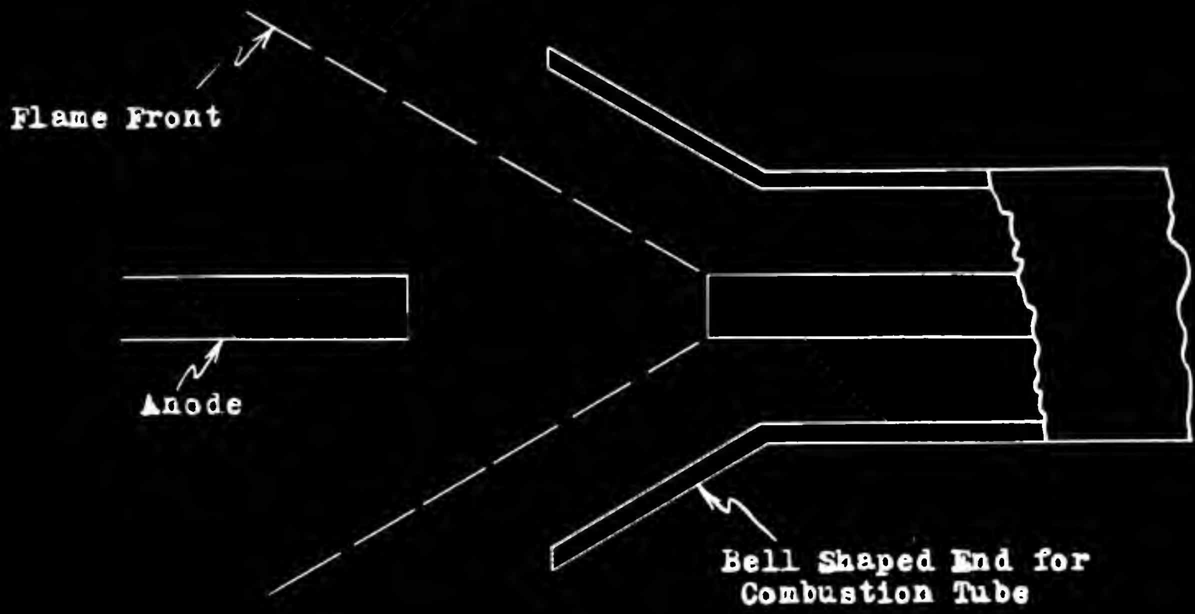
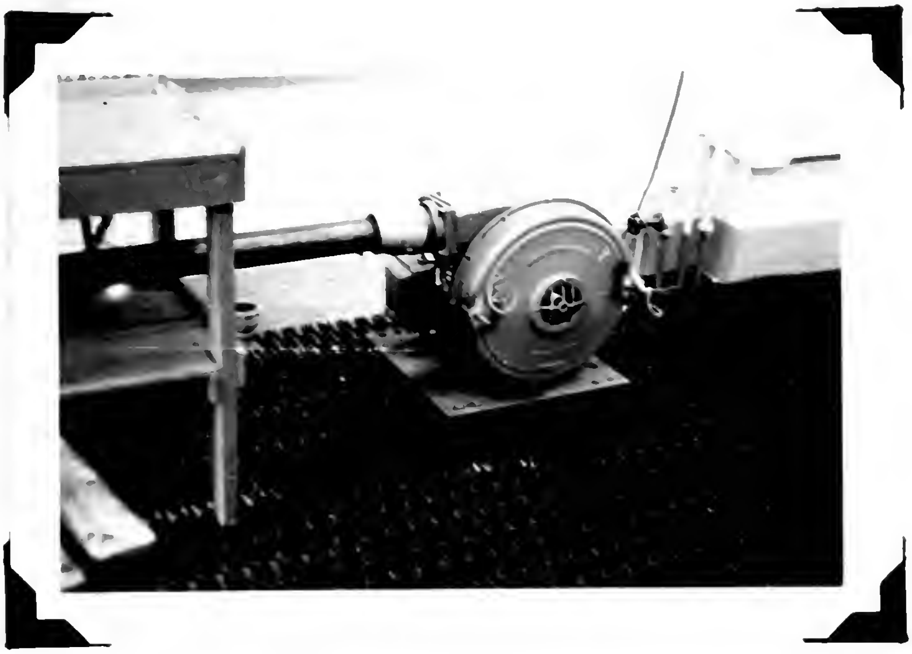


FIG. 12

Suggested Apparatus To Be Used To Increase Ion Concentration

PHOTOGRAPH 1 Appearance of Flame

PHOTOGRAPH 2 Side View of Flame

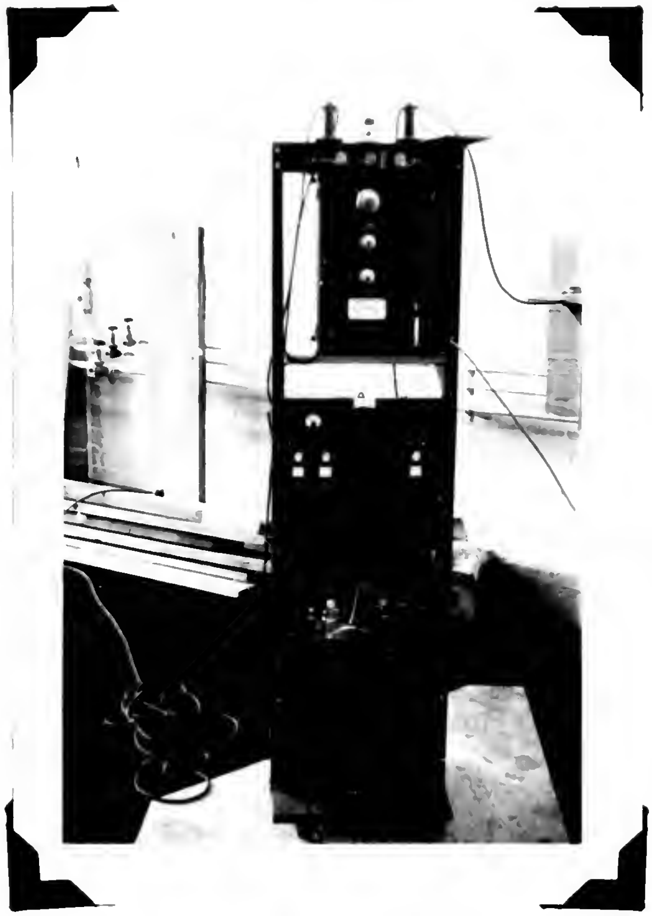


PHOTOGRAPH 3 View of Air Supply Blower

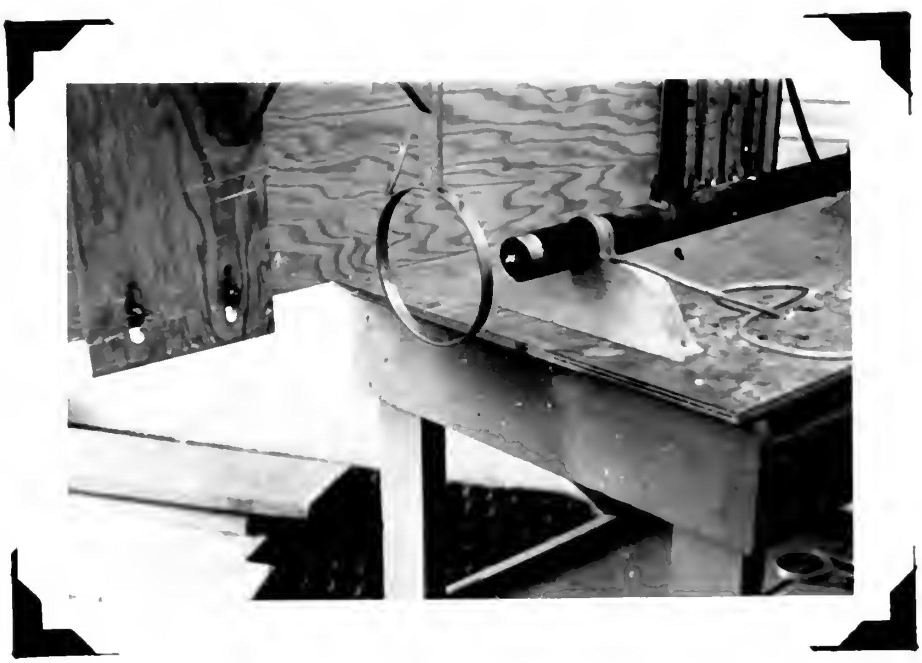
PHOTOGRAPH 4 View of Mixing Chamber and
Air Supply Control Valve

PHOTOGRAPH 5 Fuel Tank, Metering Orifices and Gases

PHOTOGRAPH 6 View of Combustion Tube and 3" Diameter Anode Ring



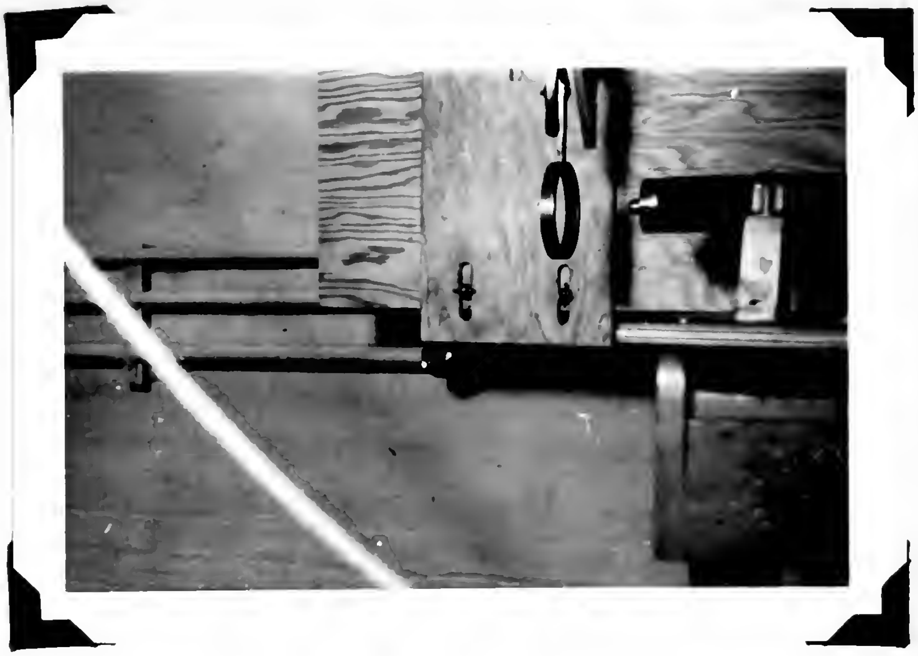
PHOTOGRAPH 7 Electrical Supply Apparatus



PHOTOGRAPH 8 Combustion Tube, Flameholder
and 6" Diameter Ring Anode

PHOTOGRAPH 9 6" Diameter Ring Anode, Flameholder, and Combustion Tube

PHOTOGRAPH 10 3" Diameter Ring Anode, Flameholder, and Combustion Tube.



PHOTOGRAPH 11 3" Ring Anode, Flameholder and Combustion Tube